

NASA TT F-11,650

# PECULIARITIES OF AURORAL RADAR REFLECTIONS AND THEIR CONNECTION WITH THE MAIN GEOMAGNETIC FIELD AND IONOSPHERIC CURRENTS

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Translation of: "Ocobennosti avroral'nykh radiootrazheniy i  
svyaz' ikh s postoyannym magnitnym polem i ionosfernymi tokami"

Academy of Sciences USSR, Soviet Geophysical Committee, Section IV  
of the IGY Program, Aurora, No. 12, Nauka Press, Moscow, 1965,  
60 pages

\$3.00  
.65

FACILITY FORM 602

N 68-24394

(ACCESSION NUMBER)

70

(PAGES)

(THRU)

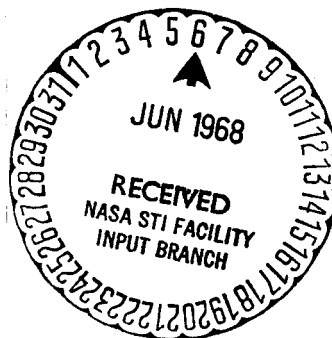
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(CATEGORY)

(NASA CR OR TMX OR AD NUMBER)



NATIONAL AERONAUTICS AND SPACE ADMINISTRATION  
WASHINGTON, D.C. 20546  
MAY 1968

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## INTRODUCTION

The physical theory on so-called auroral<sup>1</sup> radar-reflections from the high-latitudinal ionosphere, from 30 to 1000 MHz, involves two principal problems. The first concerns the mechanism of reflection or scattering, with the aid of which we could explain the origin of echo-signals at given frequencies, starting with the accepted values for the electron density in the ranges of auroral ionization. The second is related to an interpretation of the characteristic spatial and time features for the type of reflections being studied; an examination of this should show what importance the auroral radar-reflections have in the complex of the electromagnetic processes developing in the magnetic field and the ionosphere of the Earth during periods of their interaction with Solar plasma matter. /5\*

A large number of theoretical studies, among which we should single out the studies by G. Booker [1], D. Moorcroft [2], and V. I. Pogorelov [3], have been concerned with the first problem; several attempts were made for a direct experimental study (mainly by P. Forsyth et al. [4-6]). We will not be concerned in this paper with the first part of the problem, i.e., the problem concerning the mechanism of reflections and the assumptions connected with this on the absolute value for electron concentrations which cause the formation of reflected signals, or on the dimensions of the discontinuities in which the incident electromagnetic waves are scattered. We will attempt to sum up the available data on the spatial and time characteristics of auroral reflections for the principal stations in the northern hemisphere, and to obtain definite conclusions on the rules to which, obviously, these characteristics are subject. Despite the large number of works on the radar study of ionization in the ranges of aurorae in the northern hemisphere, a generalized analysis of the results, as far as we know, still has not been published.

The starting point for our discussions will be Chapman's concept of a mirror-like or (in application to radar systems with combined transmitter and receiver) orthogonal reflection. It is well known that a corresponding explanation for the foreshortened sensitivity of auroral radar reflections was given in 1953 by S. Chapman [7] on the basis of an interpretation given somewhat earlier by N. Herlofson [8] in analogy with mirror-like reflections from meteor trains. However, in the case of auroral reflections, the anisotropy

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<sup>1</sup> We will use this term for the sake of brevity in description.

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the discontinuities is determined by the behavior of the perturbed plasma in the Earth's magnetic field, and not by the trajectory of the ionized particle (although such an interpretation, in principle, is possible). The range for the anisotropy of the microdiscontinuities, which arise as a result of the drifting and perturbed movements in the upper atmosphere, is limited by the obvious condition that the gyrofrequency of electrons in this range must be much less than the frequency of electron collisions. Calculations which conform fairly well with each other result in a value for the lower margin of this range on the order of 75 km (see, for example, [9,10]). The drift velocity of the electrons in the *E*-range of the ionosphere, calculated along the magnetic lines of force, and considering the Coulomb interaction with ions, exceeds the velocity of the cross-sectional drift by two orders [9]. /6

The meaning for "the orthogonality of reflections" as applied to auroral ionization is usually treated in a somewhat less strict sense than in the case of reflections from the meteor trains. In both cases, of course, there is a certain divergence from the mirror-like quality of the reflection which expresses essentially a definite scattering diagram. Usually, in reflection from a meteor train, the diagram has a width less than half a degree, since the length of the train, as a rule, exceeds the diameter of the first Fresnel zone to a great degree. In the case of auroral ionization, the diagram of the scattering is calculated by the minimum width of half a degree only under the most advantageous conditions. This is linked with the fact that the lengthwise dimensions of the discontinuities exceed the cross-sectional ones only by a factor of 1-1.5. Therefore, the orthogonality of the reflections in the case of auroral ionization will be understood in the future as the sufficient closeness of the reflection to a mirror-like one, or the sufficient narrowness of the diffusion diagram. This tendency toward a mirror-like quality can be different in different cases.

The interpretation of the foreshortening features of auroral radar reflections as a factor which is unambiguously linked with the anisotropy of the microstructure in the ionosphere discontinuities has predominance in the literature at the present. Some of the other alternative hypotheses proposed by various authors, obviously, are only of historical interest at the present.

One more fundamental condition which will be treated in this paper as the basis for most of the discussions is the experimentally established fact of the stability of the heights which give auroral reflections. The reliability in determining the height of the reflecting range (the meaning of layer in this case needs certain stipulations) is closely connected with the degree of distinctness of the foreshortening effect. An overwhelming majority of measurements shows that the ranges for auroral reflection formation is near the *E*-range of the ionosphere, mainly from about 100 to 110 km [11]. This is valid for stations of different latitudes and different hemispheres. As an example of an accurate determination

of the heights and slight variation in their values, we can mention the studies by B. Currie, P. Forsyth, and F. Vawter [12] (Saskatoon, North America, 1953,  $110 \pm 6$  km); by R. Unwin [13] (New Zealand, 1959,  $110 \pm 3.1$  km); and by K. Bullough [14] (Antarctica, 1961,  $106 \pm 2$  km). In a large number of studies, the variations in heights of about 100-110 km are greater, while these cases refer mainly to observations at high latitudes. It is not completely clear at the present whether we are involved with inaccuracies in measurements or whether the diversion has a more fundamental character.

Calculations for the geometry of the reflections, published by Chapman [7] in 1953, were made for the geomagnetic field, i.e., for the idealized central dipole. It is well known that the magnetic field measured at the surface of the Earth does not coincide with the dipolar one for the greater part of the Earth. Thus, the obvious prerequisite for direct application of Chapman's calculations to the actual conditions of most of the stations must be the assumption that the anomalies for the various types do not extend to heights on the order of 100 km and more. If this is not so, then the actually existing magnetization field at a given point in space in the ionosphere should be included in the calculations, and not the ideal field of homogeneous magnetization.

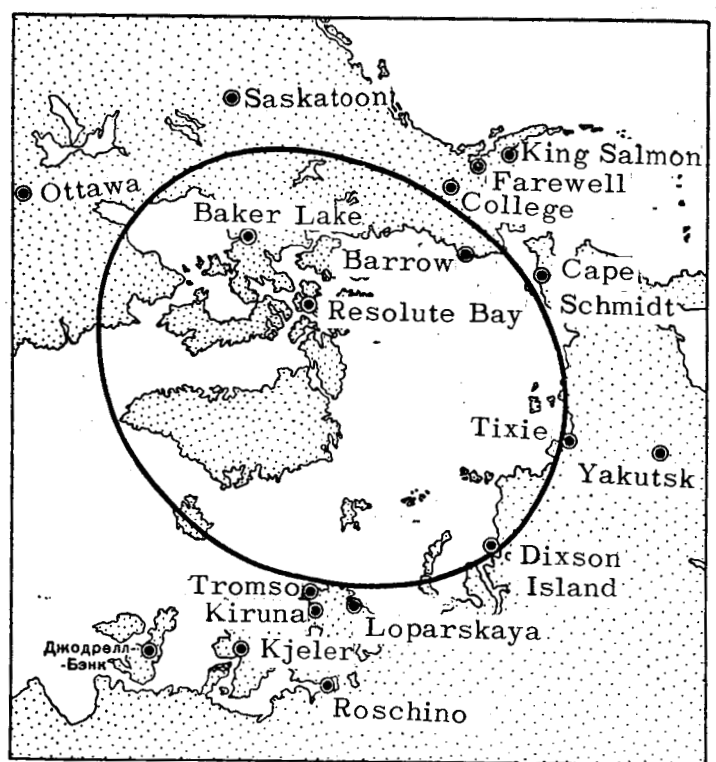


Fig. 1. Map of Distribution of the Stations for Radar Studies on Auroral Ionization. The Solid Line Separates the Zone for Maxima in Aurorae.

During the first period of studying auroral ultrashort-wave reflections, there was still some uncertainty over whether the continental anomalies extend to ionospheric heights. This was linked with a lack of data on magnetic changes at corresponding heights and with ambiguity in the assumptions on the nature of the sources of continental anomalies. At the present time we can assume that the theory of a sub-surface arrangement of sources which are responsible for continental anomalies is obviously more correct than the theory of surface stratification of the perturbed masses. Thus, for example, the lines for the observation in the third Soviet artificial satellite [15,16] indicate that these anomalies increase with height practically as rapidly as the field of homogeneous magnetization. Therefore, in interpreting the auroral radar reflections, we must necessarily calculate the real field at a given point in space, and not the ideal field of a central dipole. Moreover, this calculation is very simple, since at depths of stratification for sources of universal anomalies on the order of 1000 km, the difference from the real field at a height of 100-120 km from the field at the Earth's surface becomes almost imperceptible.

In this paper we will examine the problems in interpreting the results of radar observations by calculating the structure of the real field of the Earth. The material being analyzed will be limited, basically, to the data relating to the IGY and the previous period. We will examine only the northern hemisphere. The data from stations in the southern hemisphere will be brought in only for the sake of illustration. The geometric conditions for reflection, and their connection with the structure of the constant magnetic field in the sub-arctic and arctic regions, will be analyzed in the first section. In the second section, we will examine /8 the diurnal path of the reflections, and we will attempt to find some connection between the diurnal path of the reflections and the characteristic of the geomagnetic turbulences at high latitudes. A list of the stations used is given in Table 1, and their location is given in Figure 1.

The materials for the stations which are cited in Table 1 are not equivalent in completeness. The distribution of the radar reflections by azimuth as well as during the course of a day is known from the first fourteen stations. Only data on the daily changes in the frequency of radar-reflection occurrences are given in the literature of the last five. Obviously, this is caused partly by the circumstance that the observations for auroral ionization were made at a definite fixed azimuth. Such observations do not provide for obtaining a reliable azimuthal picture of the radar reflection occurrences. The azimuthal distribution according to the stations in Kjeller and Tromsø is not treated in [41] and [42], which are concerned with a study of auroral ionization.

As can be seen from the bibliographical references in Table 1, the materials we use mainly in this paper are only from observations which were described in the literature, and not the preliminary data

With the exception of a small number of cases). Drawing up the necessary preliminary materials for radar observations, technically speaking, would be a fairly complicated work, since, even for the period of the IGY, these materials were far from being centralized. Considering what has been said, the authors recognize the incompleteness of their study, and consider this analysis as only a starting point.

TABLE 1

| Station       | Geomagnetic Coordinates |           | Geomagnetic Latitude | Source     |
|---------------|-------------------------|-----------|----------------------|------------|
|               | Latitude                | Longitude |                      |            |
| Jodrell Bank  | 53° .2N                 | 2° .3W    | 56° .0               | [17-19]    |
| Kiruna        | 67 .8                   | 20 .2E    | 65 .5                | [20,22]    |
| Roschino      | 60 .0                   | 29 .5E    | 56 .5                | [23,24]    |
| Loparskaya    | 68 .5                   | 33 .0E    | 63 .5                | [25,26]    |
| Dixson Island | 73 .5                   | 80 .5E    | 63 .0                | [27,28]    |
| Tixie Bay     | 71 .5                   | 129 .0E   | 60 .5                | [29]       |
| Yakutsk       | 62 .0                   | 129 .5E   | 51 .0                | [30]       |
| Cape Schmidt  | 69 .0                   | 179 .5E   | 62 .0                | [25,31]    |
| Barrow        | 71 .3                   | 156 .8W   | 68 .4                | [32,33]    |
| College       | 65 .0                   | 147 .6W   | 64 .7                | [33-36]    |
| Saskatoon     | 52 .1                   | 106 .6W   | 60 .6                | [12,37,38] |
| Ottawa*       | 45 .5                   | 75 .8W    | 56 .9                | [36,37]    |
| Baker Lake*   | 64 .3                   | 96 .0W    | 73 .8                | [36]       |
| Resolute Bay* | 74 .7                   | 94 .9W    | 83 .1                | [36]       |
| Farewell      | 62 .5                   | 153 .9W   | 61 .4                | [33]       |
| King Salmon   | 58 .7                   | 156 .6W   | 57 .7                | [33]       |
| Ithaca        | 43 .0                   | 75 .3W    | 54 .0                | [39,40]    |
| Tromso        | 69 .7                   | 19 .0E    | 67 .2                | [41]       |
| Kjeler        | 59 .9                   | 11 .1E    | 60 .0                | [41]       |

\* Dr. A. MacNamara kindly sent us the data from these stations.

# RADAR REFLECTIONS AND CONSTANT MAGNETIC FIELD

## Azimuths of Reflection

If we examine only systems with combined transmitter and receiver, then, as statistics show, the optimal distance to the range of the reflections (for all stations, average- or high-latitudinal) averages 600-900 km, and has a slight tendency to be somewhat less for the first than for the second. In azimuthal distribution, the difference between various stations is substantial. High-latitudinal stations have, as a rule, one principal azimuth for reflections, around which are centered, usually with a fairly great spread, all the remaining azimuths of reflections observed. A comparison of the data, of which we will speak in more detail later, allows us to conclude that the direction of the magnetic declination obviously determines the symmetry of the range of reflections. /9\*

For average-latitudinal stations, the direction of the magnetic meridian is not, generally speaking, the direction of the most probable occurrence of the reflections, although a symmetry is also observed relative to the field of declination in the regions surrounding the station. There are usually two mutually-symmetrical azimuths, from which the probability of occurrence for radar reflections is greater than from the direction of the magnetic meridian. On the chart of distance versus azimuth, the range of reflections has the shape of a U in this case. This result is well known and is found to be in fairly good qualitative agreement with Chapman's theory [13, 19, 43]. At the same time, it serves as a confirmation of an essential constancy for the altitude of the reflecting images and the infrequently-expressed foreshortening effect for average-latitudinal stations.

Figure 2, in which the magnetic and geomagnetic loci of orthogonal reflections for the Jodrell Bank station for a height of 100 km (according to [19]) are given, gives an idea of the shape of the reflecting range which is characteristic of average-latitudinal stations (see also Fig. 10). Curves  $Gm$  and  $M$  show the position of the loci, which are determined by the condition  $(rF) = 0$ , for the geomagnetic and magnetic field, correspondingly ( $r$  is the radius-vector of the reflection point,  $F$  is the absolute vector of the field). The curves of  $88$  and  $92^\circ$  for the real field limit the range from which reflections are possible in the case of diversion from orthogonality by  $\pm 2^\circ$  at a height of 100 km. In recording by scanning for distance versus azimuth, this distribution is fixed directly on the deflector, as we can see, for example, in the photographs made in studies by C. Watkins [19], R. Unwin [13], D. Harri-

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on [44], and others.<sup>2</sup> As we turn to those average-latitudinal stations where the  $Z$ -component of the field increases (Roschino), the shape of the locus becomes less defined.<sup>3</sup> Finally, at stations which are at high latitudes, the  $U$ -shape of the reflections range is not observed (see, for example, [25, 29]). It is true that we can see a certain similarity to the  $U$ -shape in the diagram of the azimuthal distribution in the study by R. Dyce [32] for the station at Barrow, but this is probably due to some local causes. /10

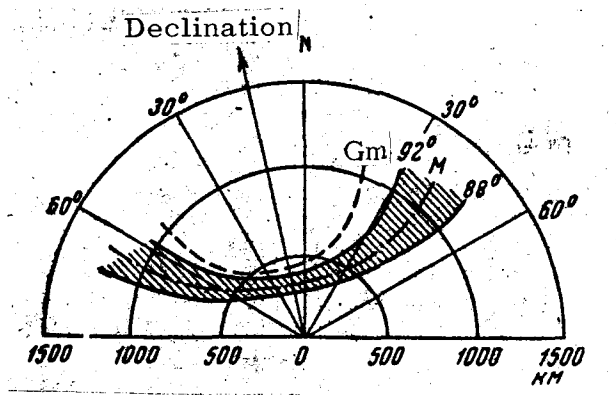


Fig. 2. Loci of Orthogonal Reflections for Jodrell Bank at a Height of 100 km. The Shaded Area shows the Range within which the Divergences from the Conditions of Orthogonality in the Case of the Real Field do not Exceed  $\pm 2^\circ$ .

of the ionosphere with discontinuities at high latitudes must differ in characteristics from the structure of the micro-discontinuities at lower latitudes. Bullough [14], who studied auroral reflections in Antarctica in the region of the magnetic pole, shows a possibility for such an explanation.

Despite the fact that Chapman's theory seems to contain a good explanation for the difference in the character of the distribution of azimuths for high-latitudinal and low-latitudinal reflections, the problem is obviously more complicated than it seems at first glance. As we will show later in the materials from the stations being examined, the geometry of the reflections at high latitudes, generally speaking, is not subject to those rules for "Chapman" reflections which are valid for lower-latitude stations. This means, obviously, that if we are not successful in our attempts to bring in refraction in order to explain the variations observed, then the structure

<sup>2</sup>In a study by Watkins [19] (Jodrell Bank) on the reflections from the ranges adjacent to the magnetic meridian, they were not clearly found, in general, although the direction of the axis in the directivity diagram (angle of the site at  $20^\circ$ ) was conducive to obtaining reflections from small distances.

<sup>3</sup>A more complete statistical treatment of the data obtained in Roschino for 1957-1960, the results of which are given in a dissertation by V.I. Pogorelov (Institute of Physics of the Atmosphere, Academy of Sciences U.S.S.R., 1963) make the  $U$ -shape range for Roschino more apparent than do the publications [23, 24] which generalize the data for a shorter period (1957-1958).

In the map shown in Figure 3, the results of measurements for the azimuths of radar reflections at fourteen stations in the northern hemisphere are compared with data on the magnetic field. The information on the azimuths was taken from the studies which are referred to in Table 1.<sup>4</sup> The data on the radar reflections were

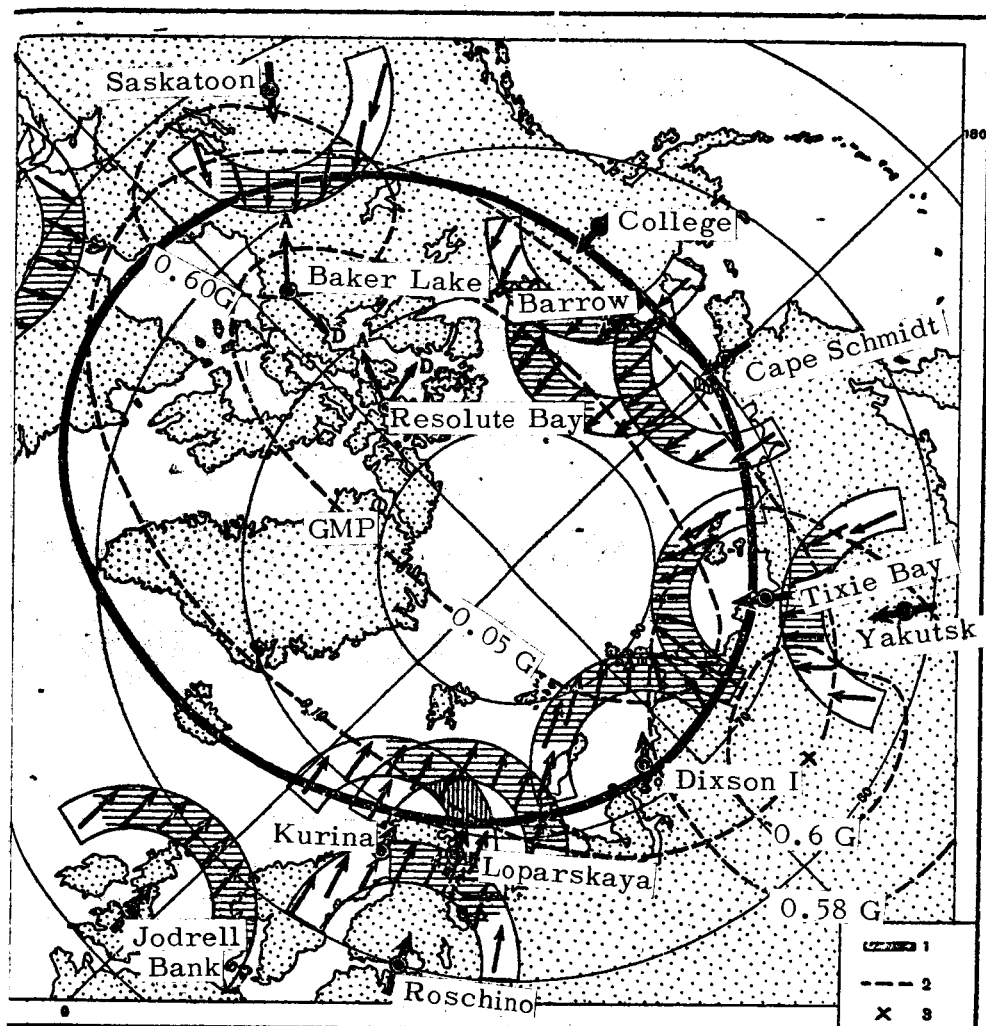


Fig. 3. Schematic Map of the Arrangement of Azimuths of Reflections for Thirteen Stations in the Northern Hemisphere. For the Stations at Baker Lake and Resolute Bay, only the Azimuths of Principal Reflections (A) and Declination (D) are Plotted. (1) Zone of Aurorae; (2) Isoline of the Vertical and Horizontal Components of the Magnetic Field; (3) Center of the East-Siberian Anomaly. Varying Data were Used for the Station at Kiruna (Different Shadings).

<sup>4</sup>We would like to express our gratitude to V.I. Yarin for his information on the precise data obtained at Yakutsk, and to Ya. G. Birfel'd for data from Loparskaya, Dixon Island, and Cape Schmidt.

intended to be given rather schematically on the map, since they are not uniformly accurate and complete (for a number of stations, for example, there are no data on the distance-versus-azimuth dependence). These data, generally speaking, refer to years with varying levels of solar activity, and were obtained with the aid of varying types of instruments. For each station, the same limits for the most probable average distances for reflections (600-900 km) are outlined by the two semicircles. Actually, the variations in distances exceed those limits and, moreover, are different for various stations. On the strength of only what we have said, it is useless to consider this too strictly. The arrows inside the half-rings we obtained show the directions of the magnetic declination, measured at the surface of the Earth. The scale for the arrows does not reflect the value for the horizontal component of the field. The points for the position of the stations also have arrows which show the declination. In order to regulate the accuracy for the total picture of the declinations field, we drew the isodynamic lines for the horizontal component with 0.1 and 0.05 G, which are fairly close to the regions which interest us. More detailed maps are given in Supplement 2 (see Figs. 22 and 23).

The shaded areas in Figure 3 in the zones of reflections correspond approximately to the interval for the azimuths, the number of reflections of which is equal to or greater than half the number of reflections at a peak, or correspond to the boundaries of the U-shaped region. It is obvious that these areas do not give precisely the actual shape of the reflecting areas. This is not essential, since we have in mind only a general evaluation of the azimuthal distribution for the reflections. Taking the possible errors for the azimuthal distributions into account, we can consider that at least nine out of the thirteen stations in Figure 3 agree fairly well in the most probable azimuths for radar reflections and in the direction of the magnetic declination in the reflection zones. Such stations are: Jodrell Bank, Kiruna, Loparskaya, Roschino, Cape Schmidt, Barrow, College, Saskatoon, and Ottawa. In all these cases, there is a good symmetry for the reflection ranges relative to the magnetic field. These five stations need a special study: Tixie Bay, Yakutsk, parts of Dixon Island, Baker Lake, and Resolute Bay. The first three stations are located near the center of the East-Siberian anomaly, and the last two are inside the zone of the aurorae. The cross indicates the center of the East-Siberian anomaly, and two isodynamic lines for the vertical component (0.60 and 0.58 G) are also given on the map.

The azimuths of the most probable angles for the appearance of reflections at the Tixie Bay station conform poorly with the picture of the magnetic declination, both for the interval at distances from 600 to 900 km and for shorter distances. The picture of the isogonic lines in the region of the Tixie Bay station and the area north of it is very complex, and the field of declinations is not uniform. If we take the declination in the zone from 600 to 900 km into account, then the region for the principal reflections at

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This station should have been centered around the azimuth at  $10^\circ$  W. The actual position for the center of the reflection range is close to  $30^\circ$  W [29]. The isodynamic lines for the horizontal component

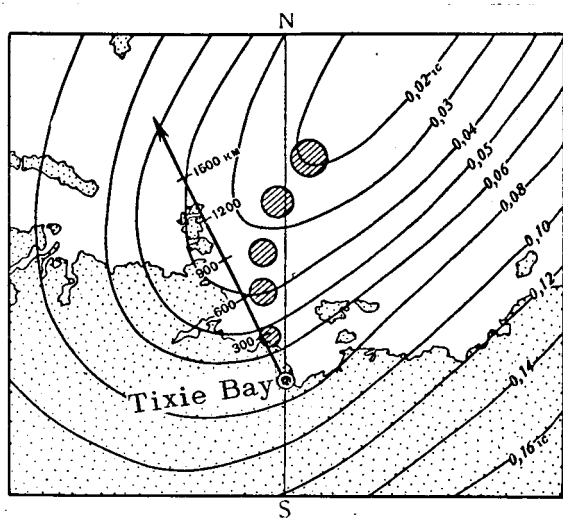


Fig. 4. Horizontal Component of the Magnetic Field in the Region of the Station at Tixie Bay. The Arrow shows the Direction for the Statistically Most-Probable Occurrence of Reflections for Observations during the Period of the IGY [29].

of the field in the areas surrounding Tixie Bay are shown in Figure 4. The arrow, fit to the scaled values for the distances (300, 600, 900, 1200, and 1500 km), shows the direction at  $30^\circ$  W. Since the picture of the field is very complicated, each distance, in essence, should have been related to its own direction for the principal occurrence of reflections (see the shaded areas).

In the region of Yakutsk and the area north of it, the field of declinations is more uniform; moreover, the center of the reflection region is located approximately  $20^\circ$  east of the direction which we would anticipate for this station. For the Dixon Island station, the reflection region is more or less accurately centered relative to the direction of the magnetic declination, if we examine its middle section. The uniformity of the field in the western section is substantially destroyed.

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The configuration of the field here is such that the occurrence of reflections from the north-western azimuths, generally speaking, is "forbidden" even in the case when it is possible to have reflection of the signals from the direction of the magnetic meridian (see Supplement 1). For all three stations, the inaccuracy in determining the principal azimuths, obviously, is not enough to explain the observed divergences from symmetry. The Baker Lake and Resolute Bay stations, which are located far inside the zone of aurorae, are characterized by the principal divergence between the direction of the radar reflections and the magnetic declination (to  $130^\circ$ ).

We can shape all that has been said into the following resume, which treats the azimuthal features of the reflections at the stations being examined.

(1) The locus shape which is characteristic for average latitudes, clearly fixed, for example, at the Jodrell Bank station, is much less defined even at Roschino, and is not observed at all at

stations which are located at high latitudes or which are near the regions for a maximum of the Z-component in the magnetic field (for example, Yakutsk and Saskatoon). As a rule, they have one basic maximum in the azimuthal distribution.

(2) For the stations around which the field can be considered fairly uniform, the azimuthal distribution for the reflection range conforms well with the conditions for symmetry relative to the direction of the magnetic field at the Earth's surface. The azimuthal distribution is obviously not linked with the symmetry of the geomagnetic field.

(3) For the stations at Tixie Bay, Yakutsk, and parts of Dixon Island, the azimuthal symmetry is destroyed for the reflection regions. They are all located close to the East-Siberian anomaly, and it is possible that this circumstance is connected to some degree with the occurrence of the asymmetry observed. Another assumption is also possible. In discussing the picture of the azimuthal distribution for reflections, we unwittingly omitted an important factor whose effect in certain cases, obviously, can greatly alter the azimuthal distribution regulated by the magnetic field. We are speaking about a consideration of the position in space for the regions of anomalous (auroral) ionization relative to the station. The southern boundary for the classical zone of aurorae, as was shown, for example, in [45], is fairly sharp. An increase in the frequency of aurorae occurrences north of this boundary entails a corresponding increase in the probability of the occurrence of anomalous ionization and a rather great discontinuity in its distribution. It is well known that the shape of the auroral zone does not reiterate the configuration for isolations of the  $H$ -component of the magnetic field (see, for example, Fig. 3). In the Yakutsk region, the direction toward the auroral zone does not essentially coincide with the direction of the magnetic meridian, which can also be caused, obviously, by a certain predominance in the occurrence of reflections from the eastern azimuths in comparison with the western ones at this station.

This hypothesis does not explain the particular features of the azimuthal distribution for Tixie Bay, but it gives us the possibility for understanding the character of the azimuthal distribution of radar reflections at stations which are located far inside the zone for aurorae.

### Altitudes of Reflecting Regions

Let us now turn to the characteristics of the magnetic field which limit the altitudes in the Chapman geometry of the reflections. Table 2 is a summary of the data (parameters of the field, angles of the site, and altitudes of the orthogonal reflections) for eleven stations for which we know the azimuthal distribution and includes the following parameters.

TABLE 2.

| $L, \text{ км}$<br>$\Delta\phi$ | 300<br>2°42'                               | 600<br>5°24'                              | 900<br>8°06'                               | 1200<br>10°48'                             | 1500<br>13°30'                           |
|---------------------------------|--------------------------------------------|-------------------------------------------|--------------------------------------------|--------------------------------------------|------------------------------------------|
| Jodrell<br>Bank                 | 0,165 0,456<br>0,362 19°54'<br>17°12' 102  | 0,154 0,467<br>0,360 18°18'<br>12°54' 170 | 0,140 0,475<br>0,295 16°26'<br>8°18' 200   | 0,130 0,484<br>0,269 15°03'<br>4°15' 207   | 0,119 0,494<br>0,241 13°33'<br>0°03' 188 |
| Rochino                         | 0,136 0,497<br>0,274 15°19'<br>12°36' 74,5 | 0,126 0,506<br>0,249 13°59'<br>8°36' 121  | 0,114 0,514<br>0,222 12°31'<br>4°24' 135,5 | 0,104 0,523<br>0,199 11°15'<br>0°27' 124,5 | 0,094 0,532<br>0,177 10°02'<br>-3°29' —  |
| Kiruna                          | 0,109 0,509<br>0,214 12°05'<br>9°25' 58    | 0,099 0,516<br>0,192 10°52'<br>5°28' 87   | 0,089 0,525<br>0,169 9°56'<br>1°31' 88,5   | 0,077 0,533<br>0,144 8°12'<br>-2°35' —     | 0,065 0,540<br>0,120 6°51'<br>-6°28' —   |
| Loparskaya                      | 0,100 0,522<br>0,192 10°52'<br>8°09' 50    | 0,091 0,531<br>0,171 9°43'<br>4°19' 76,5  | 0,079 0,539<br>0,147 8°21'<br>0°15' 68     | 0,067 0,546<br>0,123 7°00'<br>-2°12' —     | 0,054 0,553<br>0,098 5°34'<br>-7°56' —   |
| Dixon<br>Island                 | 0,060 0,574<br>0,104 5°58'<br>3°16' 23,5   | 0,048 0,577<br>0,083 4°45'<br>-0°38' —    | 0,039 0,571<br>0,068 3°54'<br>-4°11' —     | 0,031 0,570<br>0,054 3°07'<br>-7°41' —     | 0,024 0,570<br>0,042 2°25'<br>-11°05' —  |
| Tixie Bay                       | 0,053 0,592<br>0,090 5°07'<br>2°24' 20     | 0,042 0,587<br>0,072 4°05'<br>-2°03' —    | 0,036 0,580<br>0,062 3°33'<br>-6°53' —     | 0,036 0,575<br>0,063 3°35'<br>— —          | 0,040 0,566<br>0,071 4°02'<br>— —        |
| Cape<br>Schmidt                 | 0,106 0,560<br>0,189 10°42'<br>8°02' 50    | 0,085 0,565<br>0,150 8°32'<br>3°09' 61    | 0,059 0,570<br>0,104 5°54'<br>-2°11' —     | 0,040 0,574<br>0,070 4°00'<br>-6°49' —     | 0,028 0,573<br>0,049 2°48'<br>-10°42' —  |
| College                         | 0,068 0,570<br>0,119 6°48'<br>4°06' 28     | 0,047 0,575<br>0,082 4°40'<br>-0°43' —    | 0,034 0,578<br>0,059 3°22'<br>-4°44' —     | 0,020 0,574<br>0,035 2°09'<br>-8°48' —     | 0,009 0,570<br>0,016 0°54'<br>-12°33' —  |
| Barrow                          | 0,107 0,564<br>0,190 10°45'<br>8°04' 50    | 0,083 0,572<br>0,145 8°15'<br>2°51' 58,5  | 0,060 0,577<br>0,104 5°57'<br>-2°10' —     | 0,040 0,579<br>0,069 3°57'<br>-6°51' —     | 0,028 0,577<br>0,049 2°47'<br>-10°43' —  |
| Saskatoon                       | 0,113 0,603<br>0,188 10°37'<br>7°54' 49    | 0,095 0,606<br>0,157 8°54'<br>3°31' 65    | 0,076 0,609<br>0,125 7°07'<br>-0°59' —     | 0,056 0,608<br>0,092 5°16'<br>-5°32' —     | 0,040 0,603<br>0,066 3°48'<br>-9°42' —   |
| Yakutsk                         | 0,124 0,586<br>0,212 11°57'<br>7°42' 48    | 0,105 0,590<br>0,178 10°06'<br>3°06' 61   | 0,086 0,593<br>0,145 8°15'<br>-1°36' —     | 0,068 0,592<br>0,115 6°33'<br>-5°36' —     | 0,054 0,588<br>0,032 5°15'<br>-9°18' —   |

\*The Distribution of Values Inside the Boxes of the Table is:

|          |          |
|----------|----------|
| $H$      | $Z$      |
| $H/Z$    | $\theta$ |
| $\alpha$ | $h$      |

(a) The characteristics of the real magnetic field, measured near the Earth's surface, i.e.:  $H$ - the horizontal component of the field (per gauss);  $Z$ - the vertical component of the field (per gauss);  $H/Z$ , the tangent for the angle between the line of force and the vertical (cotangent of the angle of inclination;  $\vartheta$ , the angle between the line of force and the vertical (per degree)). These characteristics refer to points arranged at distances of  $L = 300; 600; 900; 1200$ ; and  $1500$  km from each stations in the direction toward the center of the reflection range. If we do not consider the Tixie Bay and Yakutsk stations, then for all the other stations this direction lies approximately in the plane of the

magnetic meridian.

(b) The calculated data on the position of the reflection points (at given distances) on the assumption of the orthogonality of the reflections, i.e.:  $\alpha$ , the angle of the reflection point for the given station (per degree);  $h$ , the height of the reflection point over the Earth's surface (per kilometer).

The uppermost row of the Table shows the distances  $L$  from the station to the point of reflection (along the Earth's surface) in kilometers and in degrees for the arc of the major circle  $\Delta\phi$ . The values  $H$  and  $Z$  were taken from the maps given in Supplement 2 (see Fig. 22 and 23); taking the inaccuracy in computations and the insufficient accuracy in the maps into account, the third number after the decimal point in the values for  $H$  and  $Z$  should be considered to be not completely valid. The values of  $\alpha$  and  $h$  for most of the stations being examined were calculated for the direction close to the plane of the magnetic meridian. The calculations were made according to the formulas given in Supplement 1. The error in the values for  $h$ , because of inaccuracy in the values for  $H$  and  $Z$  in the third number after the decimal point, does not exceed on the average  $\pm 1$  km. /15

The values for  $\alpha$  which have a minus sign, naturally, do not have any physical significance. They are kept in the table for the sake of the whole, and they show how many degrees lower than the horizon the points of orthogonal reflection are located, at a corresponding distance. We should remember that the conditions for orthogonal reflection at a western distance  $L$  are fulfilled in the plane of the meridional cross section, at a maximum altitude for the reflection point over the level of the Earth, in comparison with all the other azimuths.

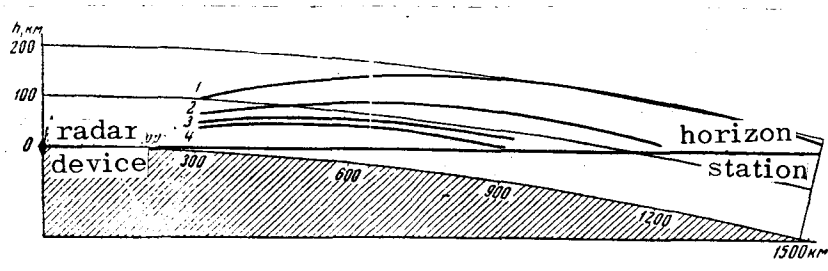


Fig. 5. Meridional Profile of the Surfaces of Orthogonal Reflection for Certain Stations

(1) Jodrell Bank; (2) Roschino; (3) Kuruna; (4) Loparskaya.

The meridional profile of the surfaces of orthogonal reflection for the stations Jodrell Bank, Roschino, Kiruna, and Loparskaya, at which the requirements for the Chapman reflection geometry are best satisfied, is shown in Figure 5. Only in two cases (Jodrell Bank and Roschino) are the surfaces of orthogonal reflection located higher than the level of 100 km. The same holds for the

station at King Salmon, whose data are shown in Table 2. For Kiruna and Loparskaya, the maximum altitudes for reflections of the surface are close to 90 and 75 km, respectively. For Cape Schmidt, College, and Saskatoon, as we can see from Table 2, the altitude of the surface reflections reaches 50-65 km in all, as a result of which the distances on the order of 900 km, at which reflections are very frequent, are already lower than the horizon of the observer. Barrow, Tixie Bay, and Dixon Island are found under conditions when the orthogonality of the radiobeam to the lines of the magnetic field is practically never achieved for any distances (the maximum altitudes calculated for orthogonal reflections are 20-28 km). Finally, Yakutsk (an average-latitudinal station located very near the range of maximum values for the vertical component, or the East-Siberian anomaly) is also found under conditions for which the requirement for orthogonality cannot be fulfilled in any way for the ionospheric altitudes.

Thus we will draw the conclusion that the reflection geometry for all the stations of high northern latitudes and for some of the average-latitudinal stations does not fit into the generally-accepted orthogonal reflection scheme which allows for only small divergences from the mirror-like quality of the reflection. We could never say that this conclusion was completely unexpected since the calculations on the basis of the real field had already been given in the literature for a number of stations to indicate a break in the orthogonality (see, for example, [46, 47] and other studies). Table 2 generalizes this result.

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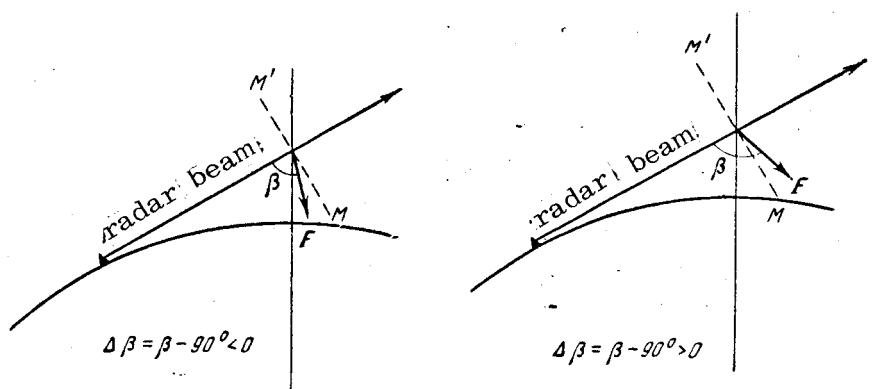


Fig. 6. Angle  $\beta$  between the Radar Beam and the Magnetic Line of Force. The Beam and the Vector of the Magnetic Field  $F$  are Assumed to be in the Plane of the Chart;  $MM'$  is Perpendicular to the Radar Beam.

Obviously, we can find ways for eliminating this contradiction by three assumptions. We can assume that: (a) the condition for orthogonality is not fulfilled by the formation of reflections observed at all the fairly high-latitudinal Arctic stations (and also at Yakutsk and Saskatoon), and the angle between the radar beam

and the magnetic line of force is always less than  $90^\circ$  for these stations<sup>5</sup>; (b) the condition for orthogonality is rather approximately fulfilled, but the structure of the magnetic field in the vicinity of the optimum reflection altitude ( $105 \pm 5$  km) differs greatly from the structure of the field at the Earth's surface; (c) the condition for orthogonality is fulfilled and the field at altitudes on the order of 100 km maintains values close to those at the Earth's surface, but the beam diverges greatly from the rectilinear distribution because of refraction, as a result of which the condition  $(\mathbf{kF}) = 0$  is fulfilled at the reflection point ( $\mathbf{k}$  is the wave vector, and  $\mathbf{F}$  is the vector of the magnetic field), and the condition  $(\mathbf{rF}) = 0$  (where  $\mathbf{r}$  is the radius-vector point of reflection from the point where the station is located) is not fulfilled.

The problem of calculating the refraction relative to the particular conditions of certain stations has been examined in the literature. This was done in detail, for example, by Ye. F. Vershinin for Yakutsk [47], and there is a schematic calculation in [41] for Tromsø. Vershinin attempted to calculate the effect of ionospheric as well as tropospheric refraction. According to his calculations, a reasonable selection of ionospheric parameters (principally the slope of the electron density and the angle of incidence of the beam for the deflecting layer) allows us to construct that beam trajectory which corresponds to the requirement for orthogonality of the beam to the line of force at the necessary altitude. An analogous conclusion was obtained in [41]. The result of these calculations, unconditionally, should be brought to our attention but, obviously, we should first consider that they explain completely that contradiction which was found in Table 2 for high-latitudinal stations.

The quantitative bases for the calculations in [41] as well as in [47] are still not reliable. This is due to insufficient knowledge of the actual slopes and the absolute concentrations of the electrons in the polar ionosphere and to the "flocculency" of the structure of this almost permanently-perturbed region of the ionosphere. On the other hand, there are those high altitudes which exceed the limits for possibilities in explanation on the basis of the refraction hypothesis. These altitudes are given in Table 2, for example, for the Jodrell Bank station (the refraction decreases the apparent altitude, but does not increase it). The observations at the Baker Lake and Resolute Bay stations, of which A. MacNamara speaks, also cannot be explained by refraction, since the reflected signals at these stations, which are located 1000-1500 km north of the auroral zone, come mainly from southern directions, and the condition of orthogonality for them can not be ful-

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<sup>5</sup>In order to avoid misconceptions as to which of the two angles between the beam and the magnetic line we are referring here, and to which we will be referring, we called this angle  $\beta$  in Figure 6.

filled for any values of the altitudes.

We will limit ourselves to these comments concerning the possible role of refraction, and we will weigh the comparative value of the other two assumptions with the aid of which we may be able to eliminate the contradiction arising in the problem on the altitudes for the reflections. Should we not consider, first of all, that, in the case of at least nine out of the eleven stations in Table 2, there are radar reflections without strict adherence to the rule for orthogonality?

TABLE 3.

| Station          | distance from the reflection point L, km |        |        |        | Station      | distance from the reflection point L, km |        |        |        |
|------------------|------------------------------------------|--------|--------|--------|--------------|------------------------------------------|--------|--------|--------|
|                  | 300                                      | 600    | 900    | 1200   |              | 300                                      | 600    | 900    | 1200   |
| Jodrell Bank . . | -0°36'                                   | +5°47' | +5°47' | +4°44' | Cape Schmidt | -9°48'                                   | -3°59' | -4°45' | -6°19' |
| Roschino         | -5 11                                    | +1 28  | +1 52  | +0 56  | Barrow.      | -13 42                                   | -7 51  | -7 17  | -8 19  |
| Kiruna .         | -8 25                                    | -1 39  | -0 43  | -2 07  | College.     | -9 45                                    | -4 16  | -4 42  | -6 22  |
| Loparskaya       | -9 38                                    | -2 48  | -2 18  | -3 19  | Saskatoon    | -9 53                                    | -3 37  | -3 32  | -4 03  |
| Dixson I.        | -14 32                                   | -7 46  | -6 45  | -7 12  | Yakutsk      | -9 02                                    | -2 59  | -3 01  | -4 34  |
| Tixie Bay        | -14 28                                   | -8 36  | -7 17  | -7 43  |              |                                          |        |        |        |

The values of  $\Delta\beta$  (divergences of angle  $\beta$  from  $90^\circ$ ) for all the stations being examined, on the assumption that the altitude for the reflections is  $h = 105$  km, are given in Table 3. The positive values for  $\Delta\beta$  indicate that the angle of incidence for  $\beta$  is greater than  $90^\circ$  (which means, first of all, that the value of the magnetic inclination at a given point is not sufficient for obtaining orthogonal reflection), and the negative values indicate that the angle of incidence is less than  $90^\circ$  (see Fig. 6). The numbers for Tixie Bay and Yakutsk correspond to the minimum values for  $\Delta\beta$  calculated for the meridional plane but not for the direction toward the center of the reflection range.

For all the high-latitudinal stations and for Yakutsk, the angle of incidence is much less than  $90^\circ$ . In this case, the divergence from orthogonality for a more advantageous distance interval (600-900 km) is expressed by an angle less than  $3^\circ$  only for two high-latitudinal stations (Loparskaya and Kiruna) and for Yakutsk. In all the other cases, it is greater. For those stations in the interval from 300 to 600 km, there is a certain optimal distance at which, at an altitude of 105 km in the meridional direction, the angle of incidence is equal to  $90^\circ$ . For the Jodrell Bank station, this distance is roughly 400 km. As the distances in the meridional plane increase, the angle of incidence between the radar beam and the line of force for the Jodrell Bank station increases rapidly up to  $95-95^\circ$  (Table 3).

According to observations by K. Watkins [19], reflections

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from distances on the order of 400 km, which are optimal from the point of view of the reflecting surface and advantageous because of the great angle of site used ( $20^\circ$ ), were not observed. We can assume that this was caused by the low sensitivity of the apparatus in these experiments. This is an essential factor, since the station is far removed from the auroral zone. However, the reflections in the meridional plane also did not occur, according to Watkin's observations, in the case of leading the virtual point toward the auroral zone. Subsequently, a divergence from orthogonality of  $\Delta\beta \approx 5-6^\circ$  greatly hinders receiving reflections. Therefore, azimuths of about  $\pm 50^\circ$  from the direction of the magnetic declination, where the angle for  $\Delta\beta$  is minimal, as Figure 2 shows, are optimal for the appearance of reflections.

For Roschino, the optimal distance for the appearance of reflections from an altitude of 105 km (according to Fig. 5 and Table 3) is close to 500 km. According to V.I. Pogorelov's data [23, 24], the position of the range for maximum probability of the occurrence of reflections in the meridional plane corresponded to a distance of about 700 km, i.e., to altitudes on the order of 120 km (see Table 2). It follows from Pogorelov's observations that a decrease in the distance from 700 to 400 km corresponded roughly to a decrease in the probability of reflections by a factor of ten. As Table 3 shows, in this case the increase in the  $\Delta\beta$  angle is roughly  $5^\circ$ . Thus, for these two average-latitudinal stations, the foreshortening sensitivity of the reflections is obviously expressed rather infrequently, and the angles of incidence for  $\beta$ , which differ by  $4-5^\circ$  from a right angle, correspond to an extremely strong decrease in the probability of reflections.

Watkins [19] considers it possible, on the basis of his observations, to calculate the foreshortening sensitivity for the Jodrell Bank station, by those values for divergence from orthogonality of  $\pm 1^\circ$ . In correspondence with these results, there are a number of other authors who have computed the foreshortening sensitivity for stations relative to small geomagnetic latitudes (for example, the data by D. Harrison [44] for the Holly Bay station: from  $\pm \frac{1}{2}$  to  $\pm 3^\circ$ ; roughly analogous data by R. Unwin [13]; R. Forsyth and C. Collins [5] found a high foreshortening sensitivity for reflections of one certain type, although they could not establish this for two types of echo).

The conclusiveness of the above and of certain other data on the high degree of orthogonality in reflections at stations of average latitudes is indisputable. Could we, without careful experimental tests, extend this rule to high latitudes? The answer can hardly be positive. For such a sharp divergence between the calculated and the average altitudes observed, as is given in Table 2, it would be difficult to exclude the idea that a non-orthogonal character in the reflections for high-latitudinal stations is possible. As we will show in the second part of this paper, the positions of orthogonality are not consolidated even if we take

the disturbances in the field at high latitudes into account. But, obviously, before we draw any further conclusions, we should carefully examine the other side of the alternative by turning to the structure of the constant magnetic field at altitudes of reflections in the polar regions.

Since we have no reason to expect any significant differences in the field at a level of 100-110 km from the one observed at the Earth's surface, while we are speaking of a uniform magnetization (the dipole in the vicinity of the center of the Earth), the problem leads to a calculation of the effect of the anomalies, and also, if we add the dynamic factors to the statistical ones, to a calculation of the effect of the ionospheric current systems.

Since the data in Tables 2 and 3 were obtained on the basis of the averaged-out maps of the magnetic field, the effect of local magnetic anomalies cannot be included in the calculations. What can be the role of the large-scale (continental) anomalies?

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As was already noted a long time ago, for example by Yu. D. Kalinin [48], during Gaussian dissociation the remanent field of the East-Siberian anomaly satisfactorily approximates the dipole with a magnetic moment of  $0.3 \cdot 10^{25}$  CGSM, which is radial to the depth of roughly 0.4-0.6 of the radius under the surface of the Earth. According to data for the year 1958, the axis of the dipole is projected on the surface of the Earth at the point with geographical coordinates of  $\lambda = 101^\circ$  E,  $\phi = 43^\circ$  N [49].

If the hypothesis on the deep-seated stratification of the sources for continental anomalies is valid, then the field of anomalies, independent of their nature, over the Earth's surface in the interval from zero to several hundred kilometers, cannot vary sharply and will be determined by the parameters of the dipole which approximates the sources. The magnetometric data, obtained with the aid of the third artificial satellite [15, 16], confirm such a picture for the structure of the anomalous field. But perhaps the picture of the field at the center of the Arctic Basin, from which come the reflections received by high-altitudinal stations, gives us grounds for doubting the usefulness of the depth theory and for accepting the assumption of a rapid change in the field from a height of 0-100 km.

The remanent field in the central part of the Arctic Basin and in the region of the geomagnetic pole is not determined by the dipole which is responsible for the field of the East-Siberian anomaly and which controls the structure of the field, in essence, throughout the entire area of the Asian continent. The same is also true in relation to the dipole which serves as the virtual source of the remanent field of the North-American anomaly. Moreover, the presumptions on a serious difference in the change of the field with altitude in Central Arctica and in other regions are obviously without foundation. We can show that a consideration

of the Iceland-Greenland negative anomaly greatly improves matters and allows us to understand the structure of the constant field of the Arctic (see Supplement 2).

The path of three components ( $X$ ,  $Y$ , and  $Z$ ) of the remanent field along the following two geomagnetic meridians is shown in Figure 7: the meridian which passes through the range for the maximum of the vertical component of the East-Siberian anomaly (ESA) and the meridian which passes through the range for the maximum of the vertical component of the North-American anomaly (NAA). Both of these directions differ from that characteristic in that, within the boundaries for a significant interval of latitudes in the northern hemisphere, they coincide well with the lines of zero magnetic declination taken in relation to the geomagnetic pole.<sup>6</sup> Therefore, a two-dimensional graph satisfactorily gives an approximate picture of the field for these meridional cross-sections in the interval for geomagnetic latitudes from 10-2- to 65-70° N. One of the possible variants for an approximation of the remanent field in the Arctic is given in Figure 7 as the field with a minimum number of dipoles. For this purpose, we used a representation of the dipoles which approximates the remanent field of the East-Siberian and North-American anomalies near the ranges of their maxima and introduced a supplementary dipole which represents the Icelandic-Greenlandic negative anomaly.

As an example of the parameters of the dipoles, we took the following for the ESA: the magnetic moment of the dipole  $M_{ESA} = 0.30 \cdot 10^{25}$  CGSM; the distance from the Earth's surface is  $0.51 R$ , where  $R$  is the radius of the Earth; the geographical coordinates of the point for the peak of the  $Z$ -component at the Earth's surface is  $\lambda = 101^\circ$  E,  $\phi = 44^\circ$  N; the maximum value for the  $Z$ -component at the Earth's surface is  $Z_{ESA} = 0.180$  G; for the NAA:  $M_{NAA} = 0.05 \cdot 10^{25}$  CGSM;  $0.4R$ ;  $\lambda = 262^\circ$  E,  $\phi = 42^\circ$  N;  $Z_{NAA} = 0.066$  G; for the IGA:  $M_{IGA} = 0.16 \cdot 10^{25}$  CGSM;  $0.5R$ ;  $\lambda = 333^\circ$  E,  $\phi = 70^\circ$  N;  $Z_{IGA} = -0.100$  G. The axes of the dipoles are considered oriented along the radii of the Earth.

In selecting the parameters of the dipoles, the arbitrary

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<sup>6</sup>On the geomagnetic ESA meridian, the values for declination (E or W) do not exceed several degrees in the expanse from the magnetic equator to approximately 60° N for the geomagnetic latitude (about 70° N geographically), and, further, up to 65° N for the geomagnetic latitude, they do not exceed the limits of values of 20° E. The projection of  $X$  differs from the projection of  $H$  in this case by not more than 5-6%. On the geomagnetic NAA meridian, the picture is roughly analogous: up to geomagnetic latitudes of 50-55° N, the declination does not exceed several degrees, and at 70° N (geomagnetic) it reaches values of 15-20° W. The position of the zero isogonic lines (relative to the geomagnetic pole) is roughly given in Supplement 2 (see Figs. 22 and 23).

element is not eliminated. We can consider that the path of the approximating curves shown in Figure 7 in first approximation conforms rather well with the path of the remanent field almost throughout all the geomagnetic meridians selected. We can be convinced

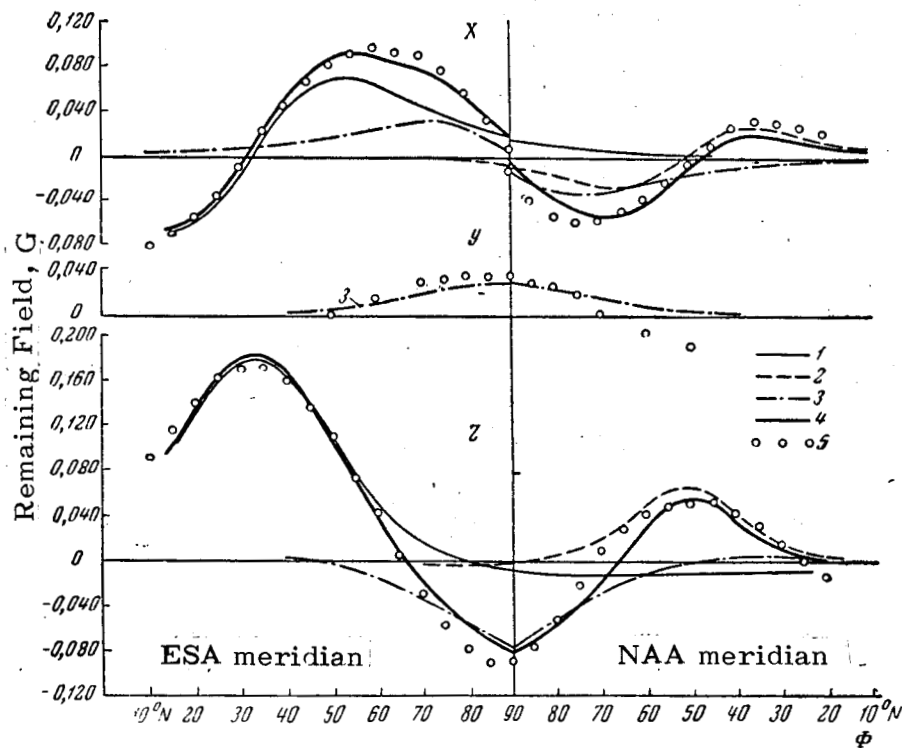


Fig. 7. Approximation of the Remanent Field for the Geomagnetic Meridians of the East-Siberian (ESA) and North-American (NAA) Anomalies with the Aid of the Fields of Three Deep-Seated Dipoles. (1) ESA Dipole; (2) NAA Dipole; (3) Dipole of the Icelandic-Greenlandic Anomaly (IGA); (4) Resultant; (5) Remanent Field.

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that the combination of these three dipoles is more or less satisfactorily described not only by the remanent field on the ESA and NAA geomagnetic meridians including the region of the geomagnetic pole, but also by the field at a number of other points of the Arctic Basin. The X- and Z- components of the remaining field have a value which is close to correct on the IGA geomagnetic meridian at higher latitudes of the Arctic. But on this meridian, as it moves toward the South, it begins rather rapidly to show the effect of negative anomalies not included in the diagram being studied, which is useful for the ESA and NAA meridians (we are speaking about the African anomaly and the minimum of the remanent field in the region of the Aleutian Islands; see Supplement 2, Fig. 24).

The analysis which we have just described does not pretend, of course, to be an adequate or exhaustive description of the field

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for the Arctic Basin. But this analyzed example shows, as we are assuming, that the basic structure of the field in the Arctic in first approximation can be described with the aid of a combination of deeply-stratified dipoles. This means that there are practically no grounds for assuming that there is a sharp difference in magnetic fields at the center of the Arctic, at altitudes of 100-120 km, and at the Earth's surface. The structure of the constant field at ionospheric altitudes and in the central ranges of the Arctic must be roughly the same as that at the level of the Earth's surface. The authors of a number of other studies have also drawn analogous conclusions (see, for example, [22]).

Thus, the results of our analysis of the azimuthal distribution of altitudes of auroral reflections and the structure of the constant magnetic field in the Arctic can be formulated in the following way. The real constant magnetic field at altitudes of the *E* region in the ionosphere is definitely regulated by the azimuthal distribution of the reflections. However, a calculation only of the constant field is insufficient for explaining the limits for the theory of orthogonal reflections by the facts of the altitudes observed for the reflections occurring in the central part of the Arctic as well as in the vicinity of the auroral zone.

# RADIO REFLECTIONS AND VARIABLE MAGNETIC FIELD

## Fundamental Properties of the Flow of Magnetic Disturbances Near the Auroral Zone

In the preceding, we discussed the characteristics of a constant magnetic field which can be used to explain the mean statistical picture of the distribution of USW reflections in the Arctic. It may be assumed that the field of universal anomalies, which causes considerable distortion of the structure of the geomagnetic field in the region of the Arctic near the Pole, are apparently not responsible for the anomalous distribution of the azimuth of reflections at the Tixie and Yakutsk stations and therefore have nothing to do with the altitude of the reflections at stations located at high altitudes. It is quite clear, however, that even in this case we would not have a comprehensive explanation for the entire picture of the phenomena even if the required agreement were found. /22

The essential characteristics of auroral USW reflections are their sharply pronounced lack of constancy (more or less systematic, but also completely sporadic variations with time; fluctuations of the azimuth, intensity, signal shape, etc.) and the clear relationship to magnetic disturbances. In other words, the characteristic feature of these reflections is their dependence upon the varying magnetic field of the Earth and the phenomena of the occurrence of auroral ionization. The problem of this relationship has been discussed at length from many points of view in the literature; in fact, it is the central theme of the majority of papers which discuss radar observations of auroras (both experimental and theoretical). In the present paper, we wish to discuss only a few aspects of this problem.

Let us consider the diurnal variation of radio reflection. The general regularity which is characteristic of both high-latitude and relatively low-latitude stations (located at distances on the order of 1000-1200 km from the auroral zone in the direction of the equator) consists of a sharp reduction in the number of auroral radial reflections during the daylight hours and a practically complete disappearance of these reflections during the hours close to local noon. There are exceptions to this rule [22,35,41,50 et al], but they do not appear to be specific [51].

It should be mentioned that radar reflections during the daylight hours occur at several stations in the auroral zone primarily during the summer months.

Although differences in apparatus can exert a considerable influence on differences in the diurnal variation and the intensity of radar reflections at the various stations, nevertheless

is possible to detect objective differences which are characteristic of individual stations, with a sufficient degree of reliability. They are characterized primarily by the number of fixed maxima in the occurrence of reflections, as well as an incomplete identity in the distribution of the maxima with time. Table 4 shows the positions of the diurnal maxima for 19 stations (according to the data given in the literature and supplemented by materials from the MTsD).

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TABLE 4

| Station       | Frequency<br>in MHz | Hours of Maximum<br>Probability of<br>Occurrence of Re-<br>flections, in Lo-<br>cal Geomagnetic<br>Time | Period of<br>Observations    | Source   |
|---------------|---------------------|---------------------------------------------------------------------------------------------------------|------------------------------|----------|
| Kiruna        | 30                  | 2300-0100                                                                                               | 1950-1952                    | [20]*    |
|               | 41                  | 1600-1700;<br>2400-0100                                                                                 | 1962                         | [22]     |
| Loparskaya    | 72                  | 2300-0100                                                                                               | 1957                         | [26]     |
| Dikson Island | 73                  | 2100-2200                                                                                               | 1958                         | [31]     |
| Tixie         | 75                  | 2200-2400                                                                                               | 1958                         | [31]     |
| College       | 216                 | Around Midnight                                                                                         | 1957-1958                    | [35]**   |
|               | 41                  | 2130-2230                                                                                               | 1958                         | [33]     |
| Cape Schmidt  | 73                  | 0530-0730                                                                                               |                              |          |
|               |                     | 0600-0800;<br>1500-1700;<br>2200-2300                                                                   |                              |          |
|               |                     |                                                                                                         | 1958 (April,<br>June-August) | [31]***  |
| Tromso        | 40                  | 1600-1700;<br>0500-0600                                                                                 | 1958 (July-<br>August)       | [41]**** |
| Barrow        | 41                  | 2030-2130                                                                                               | 1958                         | [33]     |
| Farewell      | 41                  | 0300-0400                                                                                               | 1958                         | [33]     |
| Baker Lake    | -                   | 1930-2130                                                                                               | Winter 1957-<br>1958         | [36]     |
| Resolute Bay  | -                   | 0700-0900                                                                                               | Winter 1957-<br>1958         | [36]     |
| Jodrell Bank  | 72                  | 1800-1900;<br>0100-0200                                                                                 | 1949-1959                    | [19]     |
| Roshchino     | 72                  | 1800-1900;<br>0200-0300                                                                                 | June 1957-<br>March 1958     | [24]     |
| Yakutsk       | 73                  | 1600-1700;<br>0300-0400                                                                                 | 1958                         | [30]     |
| Saskatoon     | 56                  | 2000-2200;<br>0600-0800                                                                                 | 1948-1952                    | [37]     |
|               |                     | 2300-0200;<br>0500-0600                                                                                 | Winter 1957-<br>1958         | [36]     |
| Kjeler        | 40                  | 2000-2100;<br>2400-0100                                                                                 | October 1957-<br>May 1958    | [41]     |
| King Salmon   | 41                  | 1900-2000;<br>2400-0400                                                                                 | 1958                         | [33]     |

TABLE 4 (Continued)

| Station | Frequency<br>in MHz | Hours of Maximum<br>Probability of<br>Occurrence of Re-<br>flections, in Lo-<br>cal Geomagnetic<br>Time | Period of<br>Observations    | Source       |
|---------|---------------------|---------------------------------------------------------------------------------------------------------|------------------------------|--------------|
| Ottawa  | 40                  | 1900-2100;<br>0100-0200<br>1700-1900;<br>2400-0200                                                      | Winter 1957-<br>1958<br>1957 | [36]<br>[37] |
| Ithaca  | 50                  | 1700-1800;<br>2400-0200                                                                                 | 1952-1954                    | [40]         |

\* The results given in [21] are for studies of reflections at 73 MHz, using the two-position method (transmitter at Kem, receiver at Kiruna). Due to the conditions under which the devices were installed, the region of the reflections turned out to be located only slightly to the north of the auroral zone. The diurnal variation of reflections is more characteristic of the condition at stations located at middle latitudes: in addition to the nocturnal maximum, often divided by a minimum occurring around midnight, there is an intense maximum during the hours following noon. This distribution agrees generally with the interpretation which is given in the present paper for the reflections observed at stations located at middle latitudes. A detailed discussion of the method of two-position observations is not involved in the subject matter dealt with in this article.

\*\* Distribution of reflections at a frequency as high as 216 MHz is probable but is not completely in accord with the distribution at frequencies of 30-73 MHz, used by the other stations. The maximum around midnight is related to the so-called discrete reflections at a frequency of 216 MHz, which have the character of diurnal distribution, analogous to the distribution of reflection at lower frequencies. The diffuse echo at this frequency, according to [35,52], is mainly observed during the day.

\*\*\* In June and July, three maxima were observed while in April and August only two were observed (at 0700 and 2300). Observations at this station are also characterized by the fact that reception of reflected signals was recorded during all of the 24 hours.

\*\*\*\* These data were obtained during the period of approximately one month of observation during the summer.

The Table reveals a rather obvious tendency which is disturbed only insignificantly by individual deviations: the stations at middle latitudes are characterized by two maxima in the diurnal pattern of reflections, separated by a pronounced minimum; the stations located near the auroral zone have one, two, or even three maxima, with a maximum near midnight occurring at practically all of these stations. One maximum around midnight is observed at the following stations: Loparskaya [26], Farewell [33], Barrow [32,33], Tixie [29], Dikson Island [27]. One maximum is observed at Kiruna according to the data in [20], while according to the data in [21,22] there are two. At College, there is one maximum according to [37,53] and two according to [33]. Finally, for those stations at which observations were made only during the summertime (Cape Schmidt, Tromso [41]), the occurrence of two or three maxima is indicated. Within the auroral zones, the diurnal variations are characterized by a single maximum. In the region near the Pole, the radio reflections occur much more frequently during the hours around noon (the station at Resolute Bay, for example).

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Figure 8 shows several typical curves of the diurnal variation of reflections, characteristic of the group of stations located at middle latitudes. The details of the diurnal distribution for all stations are clearly shown in Figure 9, where the distribution of maxima is given in the following coordinates: local geo-

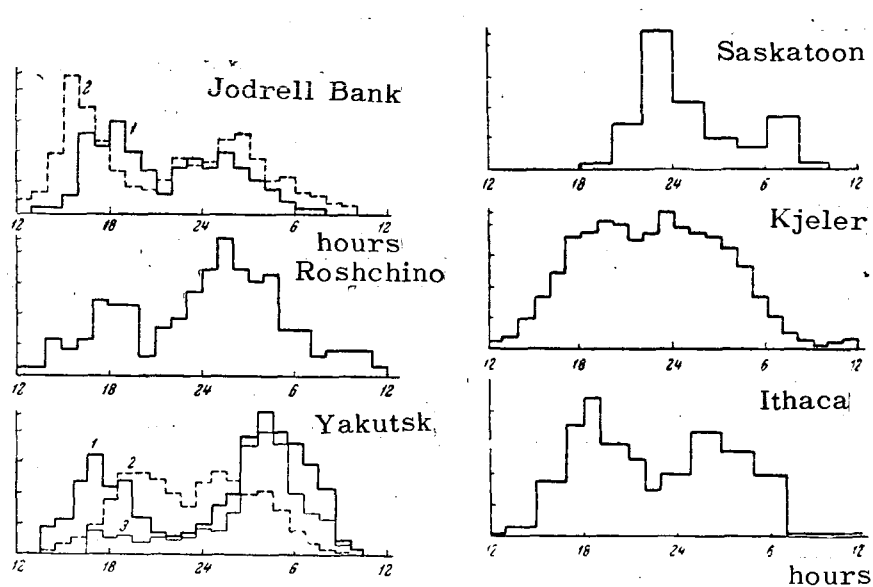


Fig. 8. Diurnal Variation of Frequency of Occurrence of Radio Reflections at Stations Located at Middle Latitudes. Jodrell Bank: 1 - According to [17]; 2 - According to [19]. Yakutsk: 1 - For All Seasons from 1958-1960; 2 - All Months in 1958; 3 - Winter Season 1958-1959. The Local Time in Hours is Plotted Along the Abscissa, While the Ordinate Shows the Number of Reflections in Arbitrary Units.

magnetic time versus the given geomagnetic latitude. It is clear that all stations located at middle latitude (except Farewell and Saskatoon, for which the given latitude turns out to be very high, record two maxima at approximately the same hours of local time (shaded rectangle 1 and 2 in Figure 9).

Regardless of the lack of completeness of the statistics, which finds its reflection in Table 4 and Figure 9, it is interesting to give to this statistical picture a certain physical interpretation. We shall attempt to do this first of all for those stations located at middle latitudes, since their basic tendency is evidently most pronounced. Naturally, this will involve a discussion of the problem of the flow systems of magnetic storms, and especially to their polar portion, which has a direct bearing on the processes at high latitudes. Apparently, there is no reason to doubt that the idealized system of flows for the entire Earth constructed by S. Chapman in the 1930's and 1940's [54], corresponding to the  $S_D$ -variations of the magnetic field, has essentially withstood the test of time. Recently, the calculations were repeated, based

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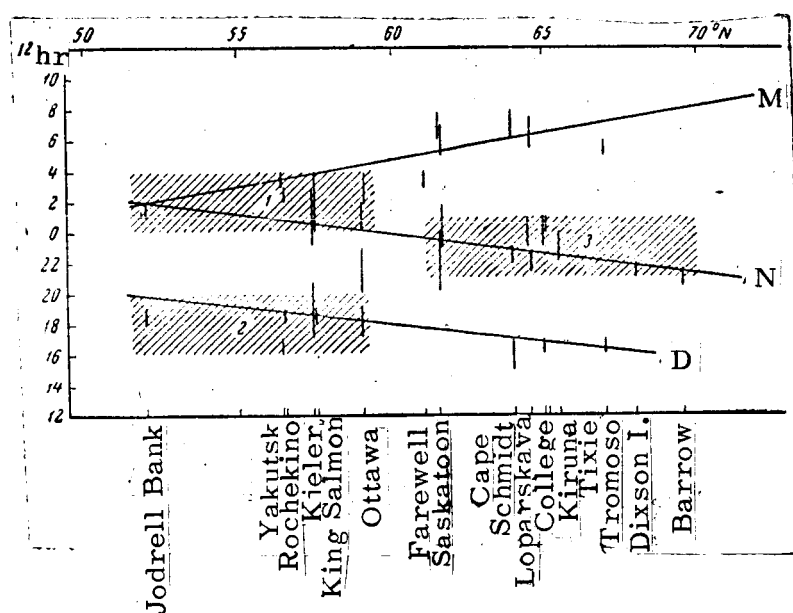


Fig. 9. Time of Occurrence of Maxima in the Diurnal Variation of Radio Reflections as a Function of the Given Geomagnetic Latitude of the Stations Along the Axis of the Abscissa, We have Plotted the Geomagnetic Latitude, While the Axis of the Ordinate Gives the Local Geomagnetic Time. The Length of the Vertical Lines Corresponds to the Lack of Determination in the Establishment of the Times of the Maxima at the Various Stations. D = Day, N = Night, M = Morning Radio Reflections. The Shaded Rectangles Represent the Periods of Occurrence of Radio Reflections: 1 = Night Hours, Middle Latitude; 2 = Daytime Hours, Middle Latitude; 3 = Night Hours, High Latitude.

on the data of a larger number of magnetic observatories than were used by Chapman in his study, and turned out to be in good agreement both with his calculations and with each other. This is true especially for the most important region, characterizing the flow system of storms, the polar ring current (polar electrojet).

Figure 10 shows the system of currents for a given moment during the widely known magnetic storm of 30 April-1 May 1933, as calculated by E. Vestine [55]. In accordance with Chapman's scheme, there was a sharply pronounced concentration of lines of flux during the storm above the auroral zone, where the current flows in the shape of two "braids" in opposite directions on the night and day sides of the Earth. The nocturnal current from East to West always has its maximum density near those points in the zone to which the hours of local time after midnight (0300-0400) correspond. The daytime current from West to East has its maximum density in the hours following noon (1500-1600).

According to Chapman and in agreement with all the calculations discussed, the current "braid" appeared to be closed primarily due to the existence of the distributed current with approximately equal density above the entire polar cap. The flow systems change their details for different storms; they change with time during the course of a single storm as well, but the characteristic concentration of lines of flux at the latitudes of the auroral zone is maintained at certain hours of local time.

Regardless of the rather wide-spread network of stations, the data from which were used in constructing charts of currents right up until the beginning of the IGY, this network was even more dense in the vicinity of the borders of the polar region than in the middle and equatorial latitudes. Within the polar basin, it was represented by only a few stations (the station on the coast of Greenland and the polar drift stations of the Soviet Union). Therefore, the agreement in the representation of the data can be considered completely reasonable, when we are talking about the highest latitudes. However, even with respect to the most sharply pronounced and carefully observed portions of the flow system of  $S_D$ -variations of Chapman in the regions near the pole, its intense semicircular currents, the consensus of opinion was incomplete until recently<sup>1</sup>. /26

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<sup>1</sup> It is interesting to note the opinion which was expressed in the book by L. Mitr, "Verkhnyaya atmosfera" (The Upper Atmosphere), Foreign Languages Publishing House, 1956, p. 361: "The currents which occur after noon and flow eastward are clearly more regular and constant than the current in the other direction." This statement is in conflict with the opinion of the majority of authors.

The data of the magnetic observations collected during the IGY have not yet been completely analyzed, but they undoubtedly will play a considerable role in explaining the final picture. Let us discuss some of the material which has already been published that deal with analysis of IGY results. These are the works by Knapp [56], Fel'dshteyn [57], Nagata, Kokubun, and Fukusima [58], and Bobrov [59].

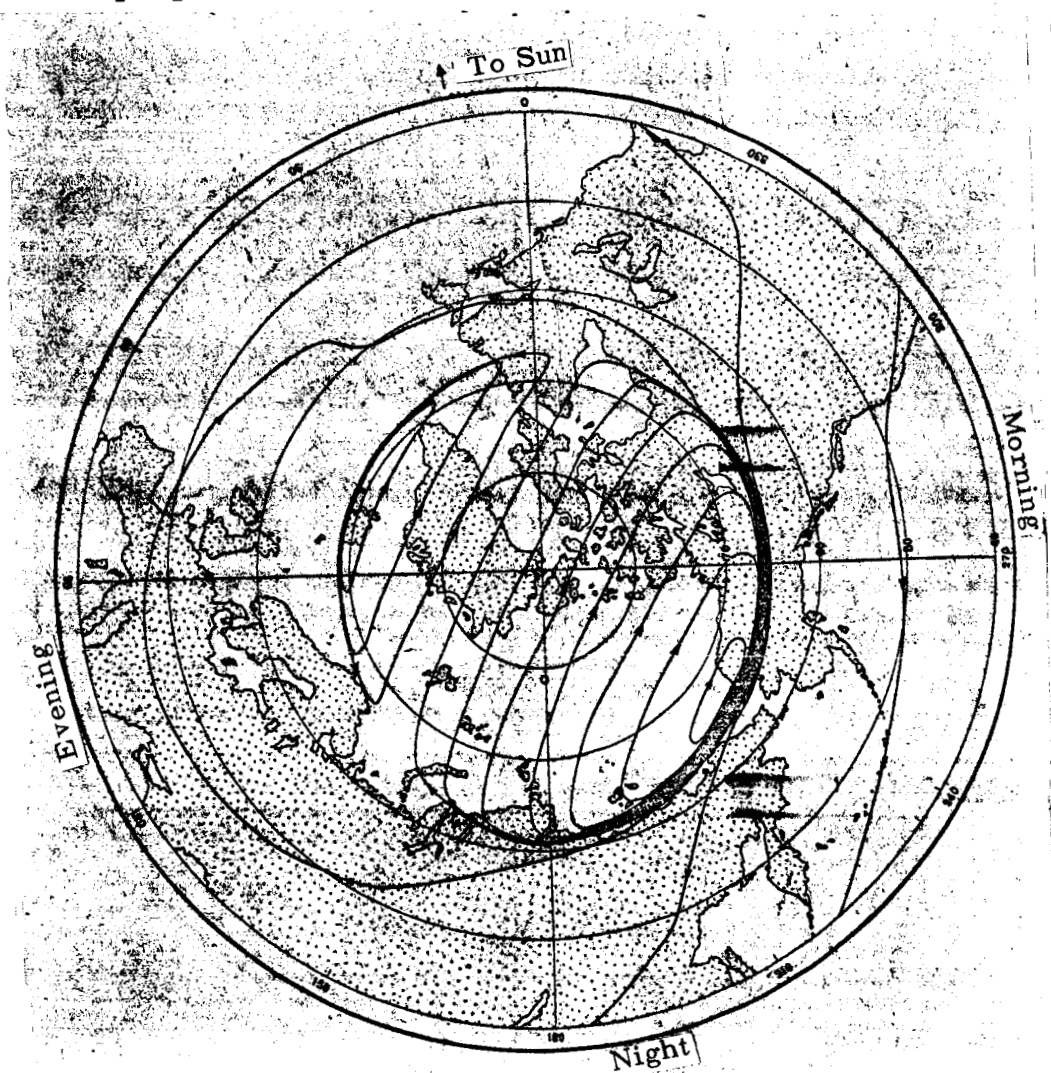


Fig. 10. System of Currents in the Auroral Zone and in the Region Near the Pole During the Magnetic Storm of 30 April to 1 May 1933 (About 1600 UT) [55].

Knapp analyzed a small number of the strongest disturbances which were recorded in the Arctic and Antarctic during the IGY, in order to determine the extent to which the system of currents in the polar regions during these disturbances agrees with the theories mentioned above. With respect to the nature of the recording

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with magnetograms, Knapp calls the disturbances which he investigated "indented bays". An analysis of nine disturbances, according to Knapp, supports the existence of a nocturnal segment of current (i.e., the "braid") in all of these cases, which is centered approximately on 0300 local time. This intense flow from East to West runs approximately along the auroral zone and shows up in the short-term (lasting from 10 minutes to 1 hour) recordings of indented bays of Knapp no less markedly than in the construction of the statistically averaged picture. The daytime "braid" of current, which occurs after noon, is on the other hand not as evident by any means.

In the disturbances investigated by Knapp, the current in the after-noon region of the auroral zone changed at different moments of time within wide limits: from a direction from West to East (as required by the averaged diagram) to the opposite; it is characteristic that even at rather closely located points, different directions of the current were frequently found. Finally, it is rather difficult to conclude on the basis of Knapp's paper what the direction was within the polar cap, where, unfortunately, the number of working magnetic stations was very small even during the IGY. Apparently, the results which he obtained are more indicative of the lack of a regular pattern within the polar cap than about the constancy of the current system similar to the distributed current of Chapman's scheme<sup>2</sup>.

The data presented in [57,58] are based on a much greater volume of statistical material than was Knapp's work, but they do not contain any analysis of the course of processes during individual storms. On the basis of data from stations which operated during the IGY in the auroral zone and the polar cap, an average picture of the flow system in the polar regions has been drawn up which is in good agreement with that which is generally assumed to be the case. The stationary character of the average direction of the current within the polar region does not create any doubts in the light of these investigations.

The extremely widespread work in systematization and analysis of data which were collected during the IGY at nearly all of the geomagnetic observatories on Earth, was performed by M. S. Bobrov [59]. The results of his work are very interesting from the standpoint of further clarification of the nature of geomagnetic disturbances. We are interested in the data which refer to the *L*-disturbances in Bobrov's classification system ("local" disturbances,

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<sup>2</sup> In fact, Knapp's results can hardly be considered conclusive, because it was found that for several stations located in the higher latitudes of the northern hemisphere, the direction of the vector of the disturbance in the horizontal plane was given incorrectly.

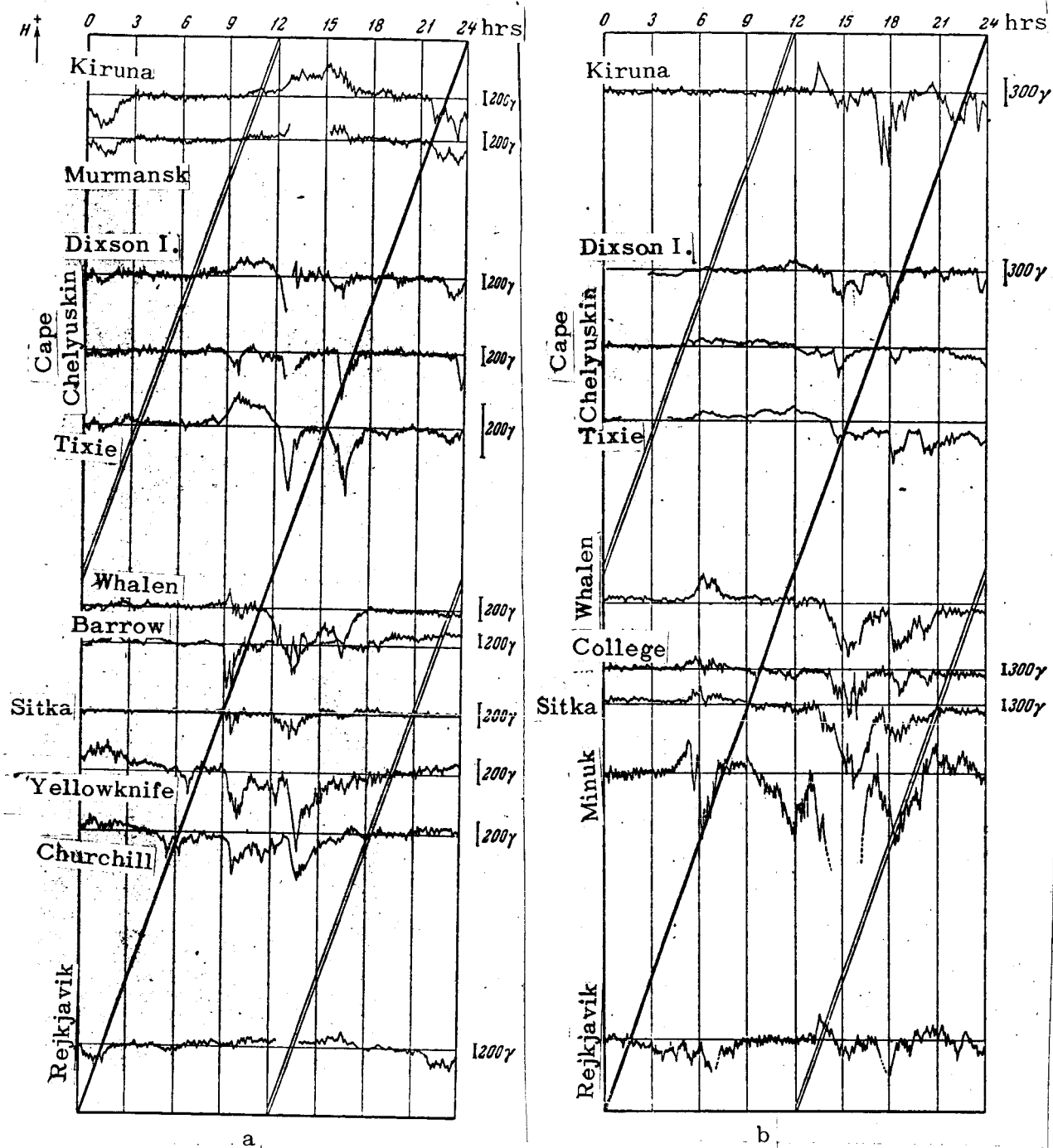


Fig. 11. Magnetograms for a Series of Stations Located Along the Auroral Zone (After M. S. Bobrov [59]). The Axis of the Abscissa Is Calibrated in UT; a = Moderate Disturbance During the Day Recorded on 12 November 1957; b = Severe Magnetic Storm of 29 September 1957. The Lines of Local Noon and Local Midnight are Also Shown.

characteristic of geomagnetic belts  $45^{\circ} < \phi < 70^{\circ}$ ). The most important feature of the  $L$ -disturbances is their locality, i.e., the spatial limitation of the period which is disturbed at a given time; a sharply peaked character, i.e., a characteristic alternation of highly disturbed periods with quiet pauses; a localization of a region of maximum intensity of disturbance along the auroral zone, where the intensity can reach 2000-3000 $\gamma$ ; their occurrence primarily on the night side of the zone, and finally, the predominantly negative sign of the  $H$  components. Bobrov supported the very important conclusion reached by A. P. Nikol'skiy [60], that the storm time variation ( $D_{st}$ ) in the horizontal component at the latitude of the auroral zone and in the polar regions is not detected. The locality, short duration, and high intensity of disturbances near the auroral zone makes it possible, as we know, to link them to a deep penetration into the atmosphere at these latitudes, of discrete clusters of corpuscles, localized in small volumes.

In Figure 11, we have reproduced in somewhat altered form, two series of magnetograms from those which appear in [59]. They list the stations which are located within the northern auroral zone. Figure 11a refers to a day with average disturbance while Figure 11b refers to the first day of the great magnetic storm, the beginning of which (according to the recordings of stations located at low latitudes) occurred approximately at 0900 UT. In plotting the curves, the recordings were shifted relative to the vertical in proportion to the geographical longitude of the stations so that the sloping lines on the graph represent lines of equal local longitudinal time (the local midnight and noon are shown on the graph). /29

In examining these two series of magnetograms, the reader will clearly see a number of very strong markings for local disturbances in the auroral zone. Especially clear is the decided predominance of negative disturbances of the  $H$  component over the positive ones, and the marked tendency of the former to appear primarily during the hours after midnight and the latter to appear after noon. However, it is completely evident that the moment of maximum intensity of the disturbance, controlled by the longitudinal position of the station, i.e., the local time, at the same time is specifically dependent on the characteristics of a given storm. A regular maximum at about 0300 local time, according to the concept of Chapman, is clearly nonexistent in the development of each of these local disturbances, although the statistical center of gravity of the negative bays definitely lies somewhere in the range from 0000 to 0900 hours. Between 0000 and 1200 hours, local time, there are no positive peaks of disturbance observed at all. All of this indicates that despite the development of a nocturnal ( $-\Delta H$ ) and less intense daytime ( $+\Delta H$ ) activity in both sections there is a more or less regular diurnal pattern, and the effect of local time is primarily expressed statistically. /30

Simultaneously, we can see that the occurrence of intense nega-

tive maxima occurs as a rule simultaneously (at exactly the same physical moment in time) at all or nearly all the extent of the half-ring of the station, located in the night-time part of the zone; the beginning of the appearance of nocturnal negative activity and the extreme values is determined to a greater degree by this peculiarity than by a strictly longitudinal factor. Thus, for example, in Figure 11b (29 September 1957) the maximum at 1500-1600 UT was followed very well from Whalen to Minuk (a distance of 2700 km) and with a considerable shift in phase, from Whalen to Dikson Island. The maximum at about 1800 UT on the same day was observed absolutely simultaneously from Dikson Island to Minuk, and with a small shift in phase was recorded even at Kiruna and Rejkjavik.

As we see from Figure 11a (12 November 1957), the drop in the horizontal component was recorded nearly simultaneously over the distance from Whalen to Churchill (3800 km), with a maximum at 0930-1000 UT; a maximum at 1300-1330 UT was recorded with a slight longitudinal shift in phase from Dikson Island to Churchill, i.e., over a distance greater than half the length of the arc of the auroral zone. At Dikson Island (and apparently at Cape Cheluskin as well), this negative maximum disturbed the daytime positive activity, which was very definitely recorded on this date at nearly all stations in the northern auroral zone.

Such a strict synchronization of the peaks of local disturbances, with a duration from half an hour to two-three hours and arising simultaneously along the length of the network of stations located close to the auroral zone, evidently must reflect a process of production and development of such a prolonged ring (or half-ring) current. This result is clearly evident and is in agreement with both the results given in the work mentioned previously [56,58] as well as with certain other studies carried out on the data collected during the IGY [61,62].

Obviously, the following conclusions are valid.

1. The moment at which the current maximum occurred after midnight, usually centered at 0300 UT according to the system of  $S_D$  variations of Chapman, is dependent to a considerable extent on the randomness of the arrival of highly nonuniform corpuscular currents on the Earth. The occurrences of a maximum (or maxima) in the disturbances, related with the formation of a polar ring current, can be expected with a high degree of probability from the hours before midnight until the late morning hours of local time. Within the framework of this diurnal regularity, the remaining details are dependent on the structure of the current.

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2. The region of concentration of the lines of force cannot be strictly linked in any way to the geographical lines determined by statistical means, which are designated as the auroral zone. Owing to various and highly random causes, it can shift both to

the south and to the north of the zone at different moments of time. However there are definite regularities which control the subsequent shift of this region during the process of the development of a storm.

3. The simultaneous existence along the auroral zones of two current systems with opposite directions is actually a frequently observed event<sup>3</sup>, although the picture as a whole is far from being a regular one and gives the impression that it is frequently disturbed by the activity of some forces which are definitely linked with processes outside of the ionosphere, and possibly at the boundary between the Earth's magnetic field and the solar plasma clouds.

It appears to us that all of the above provides further information for defining the formula for understanding the locality of the disturbances near the auroral zone. In fact, the statement that "the phase and amplitude ratio of individual peaks changes considerably with variation of the position of the observer by several hundred kilometers along the auroral zone" ([59], p. 61), cannot be considered valid for the horizontal component. The distances along the longitude, at which the disturbances are correlated with one another, appear to be very great. As Bobrov himself points out ([59], p. 53), they reach thousands and not hundreds of kilometers. In 1958, this problem was investigated in [63]. It was found that up to distances of 300 kilometers in the longitudinal direction, the variations of  $H$  change only slightly in form, but the coefficient of correlation reaches a value of 0.92.

The coincidence of local maxima along the auroral zone is highly evident in the examples given above. This refinement appears to be very real because we can use as a measure of its reliability the concept of the existence of extensive current systems during specified periods of time along large segments of the auroral zone. The duration of their existence, which can reach several hours, is not contradictory to the possible time of relaxation which must have roughly the same order of duration<sup>4</sup>.

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<sup>3</sup> It is clear that the magnetograms obtained by M. S. Bobrov [59] for two disturbed days (12 November 1957, a moderately disturbed day,  $K_{p\max} = 4$ ; 29 September 1957, a very large storm,  $K_{p\max} = 9$ ) are more indicative than the data from D. Knapp [56] of the existence in the afternoon hours of a current which leads to an increase in the horizontal component at the latitudes of the auroral zone.

<sup>4</sup> For a closed ring current with a radius equal to that of the auroral zone, and inductance  $L \approx 10^{10}$  CGSM and a resistivity of  $R \approx 10^6 - 10^7$  CGSM at a thickness of the electrojet on the order of  $100 \text{ km}^2$  and a conductance in the  $E$  layer of  $\sigma \approx 10^9$  CGSM, we have  $\tau = L/R \approx 10^3 - 10^4$  sec.

The variation with time, and the nonstationary nature of the ring current system in the auroral zone, which is clearly evident when we study the actual magnetograms, has been noted by many other investigators as well (see, for example, [64]).

### Statistics of Radar Reflections and the Role of the Polar Ring Current

In contrast to the highly comprehensive and richly detailed material on magnetic observations we have at our disposal thus far only a very small amount of statistical material for the diurnal variation of radar reflections for both the stations in the auroral zone and those located at middle latitudes. A detailed study of the results of the IGY, particularly a survey of the diurnal variation of reflection for individual days and their comparison with actual magnetograms has apparently not yet been done. Consequently, in discussing the problem of the average regular diurnal variation of radar reflections and their relationship to the magnetic activity, we are forced to consider primarily the statistical aspect of the phenomenon, based on an average picture of current systems in the auroral zone and in the polar regions. Clearly the problem of the polar regions is more complex, since all the information is less clear and full of contradictory statements regarding regularities in the processes in the polar regions of the magnetic disturbances themselves. Thus, for example, if we are forced to conclude on the basis of the analysis made by Knapp [56] that the field of disturbances and the current system corresponding to it within the polar regions do not exhibit any signs of regularity, we would come to the opposite conclusion if we were using the data in [57,58] as a basis. If we take this into account, we must try first of all to work out a method of solving the problem of the radar reflections which are received by stations at middle latitudes, since their formation must be more or less reliably linked to the existence of the current system in the auroral zone. /32

Beginning with an aggregate of existing observations, we must consider that the required condition for the occurrence of auroral reflections and their recording at a given station is a combination of at least two factors: first, a sufficient and considerably increased ionization in that part of the ionosphere from which the reflections come, and (secondly) a suitable aspect at which the observations from the station will render visible the anisotropic structure of the reflecting region as governed by the magnetic field [51]. Consideration of the geometric factor (the aspect sensitivity of the reflections) leads us to the conclusion that the optimum region of reflections in each particular case need not coincide with the region of maximum ionization above each territory considered which is involved in the disturbance. This system is complicated by the lack of stability of the actual picture of the magnetic field in the E region of the ionosphere, caused by the fluctuations in ionization and the lack of stability in the ionospheric current, as well as by additional disturbing extra-

atmospheric influences. All of this produces a lack of stability and a chaotic picture of the reflections if it is considered in detail.

The auroral zone is not a true circle, and is located eccentrically not only with respect to the geographical pole, but (to a much lesser degree) also with relation to the geomagnetic pole. This means that if we imagine a development of the polar current only with time and not in space, i.e., strictly linked to an imaginary line of the auroral zone, then the regions of maximum current density in the "braids", occurring from 0200-0500 and 1500-1800 UT, must shift in latitude during the diurnal rotation of the Earth. However, this effect is clearly neither the only one nor the principal one. The location of the zone of the aurorae as the region of their maximum occurrence is determined statistically. If we consider the process of development of a given magnetic storm, we will not only not have any basis for linking the position of the ring current with a strictly fixed line for the zone, but will also have to devote particular attention to the exact opposite aspect of the situation. The results of optical observation of aurorae during the IGY, as mentioned in the papers by O. V. Khorosheva [61, 62], and Ya. I. Fel'dshteyn [45, 57], and the information on magnetic observations contained in [64, 65] indicate the existence of an active diurnal shift of the zone of the maximum of the aurorae and the magnetic disturbance. The drift of the zone for an observer located on the surface of the Earth takes place in a southerly direction during the hours before midnight local time and in a northerly direction during the hours after midnight.

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Hence, the region of maximum frequency of occurrence of aurorae at the zenith and therefore the ring current around the polar cap undergo noticeable diurnal variations (pulsate). The amplitude of these pulsations is related in a certain way to the intensity of the magnetic disturbance. This is indicated, for example, by the noticeable shift toward the equator of the limit of occurrence of aurorae at the zenith with increasing planetary magnetic activity [65]. The existence of such pulsations seems to us to be the key to explaining certain principal essential characteristics of the diurnal variation of radar reflections at stations located at middle latitudes<sup>5</sup>.

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<sup>5</sup> The regular diurnal shift in the zone of maximum frequency of occurrence of aurorae and the southern limit of occurrence of aurorae at the zenith, as well as the analogous shift in the region of maximum of hourly mean magnetic disturbance were detected as a result of the studies of materials gathered during the IGY. In addition to these shifts, which it has been found possible to explain as a result of studies of processes on the global scale, are characteristic of the auroral zone; there are other types of motion which are detected locally. Radar methods [41, 66, 67] have clearly made it possible to draw conclusions regarding the presence of an east-west drift of ionized formations, analogous to the similar (Footnote 5 continued on page 37.)

Let us begin with discussion of the results at the Jodrell Bank station. The distance from this station to the auroral zone is about 1300 km (Roshchino about 1000, Yakutsk about 1200, Saskatoon about 700 km). The constant magnetic field around the Jodrell Bank station is characterized by the lowest values  $Z/H$  of all the stations mentioned. This means that under conditions of a quiet field, in the direction of the locator beam along the magnetic meridian, the altitudes of the orthogonal reflections will go beyond the limits of the  $E$  region of the ionosphere to distances on the order of 400 to 450 km (see Table 2).

In Figure 12, we have shown on the map the limits of the locus for the altitude of the reflection at 100 km. As in Figure 2, the shaded area which is bounded (according to [19]) by the values of deviation of orthogonality  $\Delta\beta = +2^\circ$  (the northern limit of the region) and  $\Delta\beta = -2^\circ$  (southern limit). The azimuth  $A_0$ , which is close to the direction of the magnetic meridian, nearly coincides with the direction of the shortest distance to the active zone. In first approximation, we are correct in identifying the active zone with the auroral zone shown in Figure 12. As mentioned above, under conditions of a quiet field the reflections along the azimuth  $A_0$  with retention of orthogonality are practically impossible. It is more likely that there will be an occurrence of reflections at two symmetrical azimuths, corresponding to angles of approximately  $\pm 50$  from the meridional direction  $A_0$ . The segments of the locus at these azimuths have a greater length and pass closer to the active zone than the central part of the locus. On the whole, however, in view of the distance of the Jodrell Bank station from the auroral zone, the conditions for receiving auroral reflections under conditions of a quiet field are not very favorable here, as was pointed out repeatedly in the literature (see for example [70]).

The conditions for reflection at the Jodrell Bank station, however, can be much more favorable if we take into account the development of an intense "polar current" during a magnetic storm,

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5 (Continuation) drift which is observed optically [68].

As a result of the analysis of observations of a great many magnetic bays (the elementary magnetic disturbances) at Murmansk during 1959 and 1960, M. I. Pudovkin and A. B. Korotin [69] found some interesting peculiarities of the occurrence of the mechanism of the dynamo effect during an elementary disturbance. They noticed a drift of the ionized cloud and a current stimulated in it over a wide distance from the location of the initial action of the ionizing agent. The direction of the drift, evidently caused by a transfer of air masses, clearly indicates, in accordance with the dynamo theory, the direction of the current and the sign of the magnetic disturbance. These and other local processes are not identical to global effects to which our further discussions will be related, which have an essentially statistical character.

localized in the active zone. In the corresponding direction of the current, the additional field which arises will increase the

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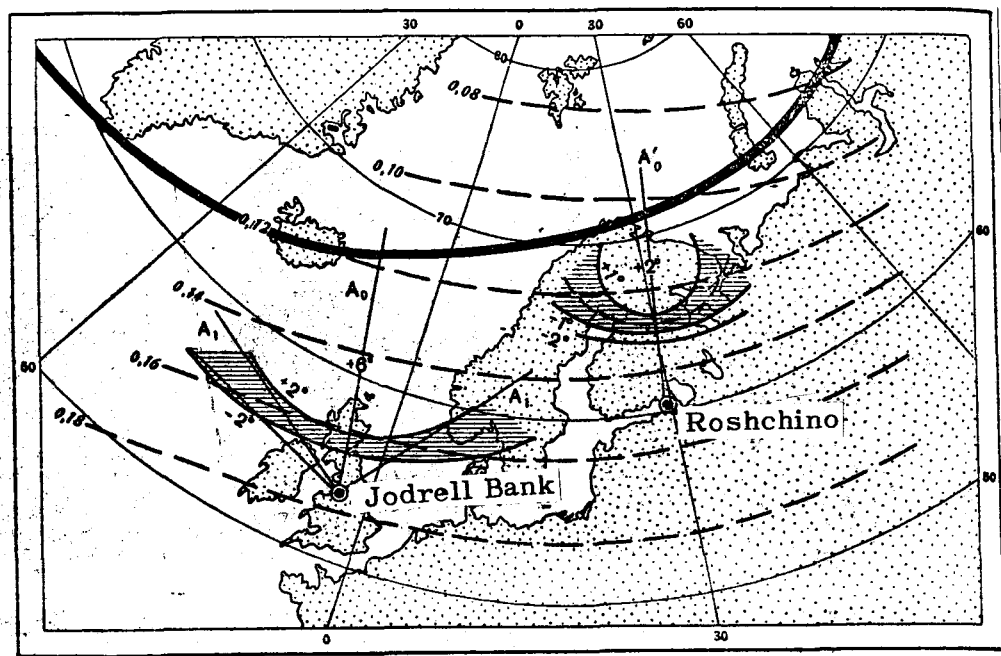


Fig. 12. Geographical Position of the Loci for the Jodrell Bank and Roshchino Stations for Altitudes of 100 km. The Heavy Line is Drawn to Represent the Auroral Zone. It is Clearly Evident that the Conditions in the Meridional Direction for the Roshchino Station Are Much More Favorable Than for the Jodrell Bank Station (At a Distance of 900 km  $\Delta\beta \approx +2$  and  $+6^\circ$ , Respectively). The Dashed Lines Represent the Isodynamic Lines of the  $H$  Component of the Constant Field.

magnetic declination at the outer (northern) limit of the locus, shifting the region of orthogonal reflections (allowed from the point of view of the aspect effect) in a northerly direction, i.e., bringing it closer to the region of increased auroral ionization (azimuth  $A_1$  in Fig. 12, e.g., correspond to the required reduction of the angle  $\beta$  by a total of  $2^\circ$  for a distance on the order of 900 km). It is clear that the decrease in the altitude of the orthogonal reflections in the regions investigated occurs in the case when the linear or quasi-linear current flows to the north of the zone of reflection in a direction from West to East (Fig. 13, 1). The result will be most effective in those regions where the value of the change in angle  $\beta$  is minimum with the presence of a required additional ionization<sup>6</sup>.

<sup>6</sup> In what follows, we shall use the terms "region of reflections" or "zone of formation of reflections", which shall be taken to mean the region in the ionosphere at the height of the  $E$  layer which is (Footnote 6 continued on page 39.)

According to the data in Tables 2 and 3, we need not expect even at very high magnetic disturbances that there will be reflections at azimuths close to the magnetic meridian. At distances of about 900 km and more, this would require a change in the angle  $\beta$  by  $5-6^\circ$  and a corresponding increase in the Z component of the field by 0.5-0.6 initial values, i.e., by 20,000-25,000  $\gamma$  which is completely impossible. With the current configuration under consideration (see Fig. 13), extending over considerable distance from the reflecting layer, and with disturbance of the component of the field at altitudes of the layer of the ionosphere, it is clear that it can be completely disregarded. This follows from

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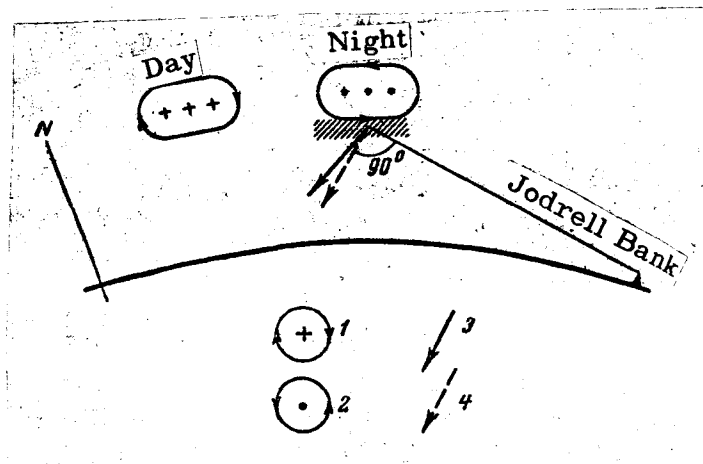


Fig. 13. Diagram of the Flow of the Polar Ring Current, Favoring Appearance of Reflections at the Jodrell Bank Station. The Closed Loops Represent the Direction of the Lines of Force of the Magnetic Field Current; 1 is a Current from West to East; 2 is a Current from East to West; 3 is an Undisturbed Vector; 4 is a Disturbed Vector.

the fact that by virtue of the conditions of transparency of the ionosphere [71], all of the horizontally extended ionospheric current systems are localized within a narrow interval of altitudes near the E layer. Hence, in forming a disturbed field at points which are sufficiently far from the point of formation in the horizontal direction, a significant role is played by the Z component. This fact has not always been considered for some reason or other in constructing the radar reflections with simultaneous observations of variations in the magnetic field (see e.g., [23, 24, 30]).

In accordance with the representation under consideration, the current system of a storm (see Fig. 10) the maximum influence of an East-

#### 6 (Continuation)

accessible to the locator beam in the first place (located no further than 1200-1300 km from the station and not closer than about 300 km if we take into consideration the principal lobe of the directional diagram) and in the second place that this region at the given moment of time has sufficient ionization in order to cause a reflection or reverse scattering of USW signals. Under these conditions, we can consider that reception of reflections at the station can actually be accomplished only under conditions of more or less strict orthogonality. In the opposite case, the zone of reflections will remain only a virtual zone of reflections, from which signals may not be received.

ern current (West to East), running to the north of the zone of reflections, must reach the Jodrell Bank Station during the period from 1500 to 1800 local time. This is in agreement with experimental results (see Figs. 8 and 9). At the same time, the magnetic observatory at Eskdalemuir recorded a maximum in the mean daily variation of the Z component of the magnetic field [17]. At approximately 2100, the number of reflections at the Jodrell Bank Station was minimal; this moment corresponds to the replacement of the daytime half-ring current by a current in the opposite direction, from East to West, i.e., a practical interruption in its continuation. Consequently, there begins a rapid increase in the current with the new direction and the sign of  $\Delta Z$  changes. If we consider that the distance of the newly produced current from the station remained as before, then this current (the direction E to W) must be responsible for the decrease in the Z component of the field, not only in the vicinity of the Jodrell Bank and Eskdalemuir Stations but also in the zone of the reflections, which leads to an increase in the altitude of the orthogonal reflections. Since this would amount to a reduction of the probability of reflections, the occurrence of a second maximum at the Jodrell Bank Station (0000-0200 hrs, see Table 4) would have been inexplicable. Hence, we must assume that during the hours of the nocturnal maximum of reflections, the current runs much more to the south than during the day.

The conditions for changing the complete vector of the field in the required direction will be optimal at a current flow (see Fig. 13) directly above the region of the reflections. Hence, the nocturnal "braid" (E to W) must be shifted in latitude by a distance on the order of 1300 km from the Jodrell Bank Station to a distance of at least 600-1000 km, corresponding to the maximum distances of the reflected signals [19]. This period corresponds to the maximum of the negative values of  $\Delta Z$  in the diurnal variation according to the measurements made at the Eskdalemuir Station [17]. Soon after local midnight, the current "braid" obviously must begin its reverse motion toward the North, inasmuch as the number of radar reflections after the second maximum is attained begins to decrease rapidly. After 0500-0600 and even until 1300-1400 local time, the configuration of the currents is not favorable for the production of reflections at the Jodrell Bank Station. This is in good agreement with the finding of a pronounced minimum on the curves plotted by T. Kaiser [17] and K. Watkins [19] for the diurnal variation of the reflections (see Fig. 8). /36

The theory of a varying field of ionospheric currents to explain the variations in the aspect sensitivity is not a new one. A number of calculations of this type were published, e.g., by V. I. Pogorelov [3]. Is this theory really in agreement with the actual possible variations in the magnetic field at altitudes of 100-110 km?

Pogorelov, using the theory of Booker [1], showed that for the Roshchino Station, the value  $\Delta H \approx 0.02$  Gauss in the zone of

the reflections is the same value which would explain the statistical distribution of the intensities of the intense reflections [3]. Roshchino, however, with respect to the altitude of the orthogonal reflections, is located in much more favorable circumstances than is Jodrell Bank (this is clearly evident from Table 2). Consequently, the required mean intensity of the disturbances which significantly broaden the locus must be greater for the Jodrell Bank Station.

In fact, if we use, e.g., a point at a distance of 600 km in the meridional plane of the Jodrell Bank Station, then the minimal value required for attaining orthogonality  $|\Delta F|$  ( $F$  is the complete magnetic vector) at an altitude of approximately 110 km at this point will be about 0.05 Gauss (5000  $\gamma$ ). This is a highly unlikely figure, especially in view of the considerable distance between the station and auroral zone. It also follows from this that, unlike Roshchino, the meridional plane of the Jodrell Bank Station need not contain reflections either only at hours of daytime (evening) maxima, but also at hours of nocturnal maxima (the E to W current is just above the region of reflection). Consequently, as we can see clearly from [19], only those parts of the locus which are distant from the center are effective. In this case, the values  $|\Delta F|$  for the broad interval of distances greater than 500-600 km can be rather small; the number decreases as the region of anomalously increased ionization moves southward during the period of the disturbance.<sup>7</sup>

An interesting illustration of the system described for Jodrell Bank can be found in an article by K. Watkins [19]. He provides magnetograms from the magnetic observatories at Eskdalemuir and Lervik for the period of the severe disturbance of 22-23 September 1957. Both observatories are located near the magnetic meridian of the Jodrell Bank Station, but Eskdalemuir is located somewhat to the south of the region from which reflections are primarily received at the Jodrell Bank Station; Lervik is considerably north of this region. The recordings for 22-23 September 1957 show almost complete similarity of the disturbance pattern for the  $H$  components at Lervik and Eskdalemuir, i.e., the same sign and shape for the  $H$  disturbance. The pattern of the  $Z$  disturbance has the nature of a mirror image for these two stations ( $+\Delta Z$  at Lervik,  $-\Delta Z$  at Eskdalemuir and vice versa). An examination of the signs and relative values of the  $H$  and  $Z$  variations permits us to conclude that the positive (daytime) burst of  $H$  disturbance may be produced by a W to E current, occurring somewhat to the south of Lervik, but rather

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<sup>7</sup> We consider it our duty to draw attention to the fact that K. Watkins in one of his later works [72] expresses in a very cautious form a suggestion analogous to ours, which links the shift toward the south by the current structure with a possibility of observing reflections at the Jodrell Bank Station.

far to the north of Eskdalemuir. The nocturnal negative burst of  $H$  disturbance was obviously caused by a E to W current passing almost above Eskdalemuir or slightly north of it. On the basis of several features of the magnetograms, we can assume that during the nocturnal hours there was a simultaneous occurrence of the E to W current to the north of Lervik as well, where it produced a slight general drop in the  $Z$  component against the background of which sharp positive peaks of  $Z$  disturbance could be seen.

The clear picture of magnetic disturbance is accompanied by a no less apparent picture of the appearance of radar reflections, also described by K. Watkins [19]. The daytime current W to E near Lervik, in accordance with the general scheme (see Fig. 13), must produce a drop in the  $Z$  component in the region of the reflection, with  $H$  having been changed slightly. In Watkins' diagram, this corresponds to the first maximum of the radar reflections (1500-1700 UT). The nocturnal current E to W near Eskdalemuir, south of the region of the reflections, must have produced a second maximum of radio echoes. These reflections are mentioned by Watkins as occurring in the period from 0300-0700 (and partly around midnight as well). The general pattern of the occurrences taking place on 22-23 September 1957 in the vicinity of the Jodrell Bank Station thus become completely understandable. It should be mentioned that approximately the same explanation for the events is given by K. Watkins, but he does not analyze the probable current pattern in sufficient detail.

Let us turn now to the other stations located at middle latitudes. The Roshchino Station has almost the same geomagnetic latitude as Jodrell Bank, but its  $Z/H$  ratio (and for adjacent northern regions) is greater than for Jodrell Bank. Therefore at all distances, the heights of the orthogonal reflection for Roshchino are less than for Jodrell Bank (see Table 2). The locus for an altitude of 100 km, calculated on the basis of the actual magnetic field, has a decidedly different shape for Roshchino than for Jodrell Bank (see Fig. 12). Along the line of the magnetic meridian (azimuth  $A_0'$  in Fig. 12), beginning at a distance  $L \approx 400$  km, the deviation from orthogonality does not exceed  $\pm 2^\circ$  at any point. The region  $|\Delta\beta| \leq 1^\circ$  is sufficiently extensive and is located sufficiently close to the auroral zone. It is quite clear that regardless of the fact that the geomagnetic latitudes are the same, the favorable conditions for production of radar reflections must occur much more frequently at the Roshchino Station than they do at the Jodrell Bank Station. Due to the lack of reliability produced by variations in the apparatus used at the two stations, and in view of the lack of standard methods of recording the signals, it is difficult on the basis of the public statistics to get a reliable support or lack of support for this fact.

With all these differences, the total picture of the diurnal variation (see Fig. 8) - the occurrence of the first maximum (1700-1800) followed by a minimum and then a second more prolonged maximum

(0100-0200) - can be explained for the Roshchino Station in the same way as for the Jodrell Bank Station. The difference consists in the fact that thanks to the very small increase in the calculated altitudes (see Table 2) above the optimal levels (100-110 km), we must expect that in its own way there would be a depression of reflections at two strong disturbances, which clearly need not be feared at the Jodrell Bank Station. We turn now to the published material from the Roshchino Station [23, 24]; we will see that the presence of depressions was in fact recorded by the observers. V. I. Pogorelov [73] used the data from his observations to construct the relationship between the number of radar reflections and the magnitude of the disturbances of the magnetic field, measured at the Voyeykov magnetic station. Pogorelov used the horizontal component of the disturbance vector for comparison ( $\Delta H$ ) and showed that

(1) radar reflections at Roshchino are observed in the case of disturbances of either sign, (2) cases of reflection with positive disturbances are relatively few, and the absolute values  $\Delta H$  are then lower in value than with negative disturbances, (3) with negative  $\Delta H$  the dependence of the probability of the reflections upon  $\Delta H$  has a maximum in the region from 0 to  $-450 \gamma$ , and (4) at  $\Delta H \approx -500 \gamma$  the number of reflections is minimal, although with further increase of the intensity of negative disturbances, the probability of the reflections again increases (see Fig. 16).

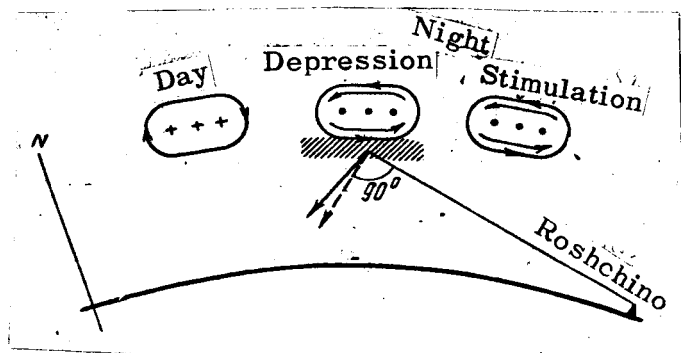


Fig. 14. Diagram of the Flow of the Polar Ring Current for the Roshchino Station and the Mechanism of Formation of a Depression in the Case of a Powerful Current (Double Arrows). The Markings Are the Same as in Figure 13.

From the point of view of the theories which have been developed, all of these details of distribution find their explanation. The negative values of  $\Delta H$ , found near Roshchino, must be the result of the flowing of an ionospheric current in the latitudinal direction from East to West, i.e., a nocturnal current in the polar ring. The correlation of the radar reflections with the negative nocturnal disturbances is clearly an indication of a drop in the altitude of the orthogonal reflections during these periods for distances of 600-1200 km. In the meridional direction, which (unlike the situation at the Jodrell Bank Station) does not appear to be so strictly forbidden for Roshchino, the decrease must take place from values of 120-140 km (see Table 2) to 100-110 km. This permits us to assume that the nocturnal current either flows directly above the zone of the reflections or appears still further to the south, situated between the observation station and the region of the reflections (Fig. 14). In the first case, the  $H$  component, "acts" as the

field of the current; however, when the current shifts to the south, the effect gradually leads only to an increase in the  $Z$  component of the field in the reflection zone. The most probable azimuth of the transition of the reflections in this case is clearly not  $A_0'$  but the azimuths around  $\pm 30^\circ$  from  $A_0'$ , since for these the required values of  $\Delta\beta$  will be minimal. Due to the considerable width of the directional diagram of the antenna in the horizontal plane, this effect is not very noticeable in practice<sup>8</sup>.

To get an idea of the true position of the currents in each individual case, it is necessary to have a detailed analysis of the magnetic data. It is possible to confirm however, that if the values of  $\Delta H$  found at the Voyeykov Station are determined primarily by the development of the quasi-linear polar ring current, then two parameters are found to be acting on the value of  $\Delta H$ : the current strength and its distance from the magnetic station. It is clear that the approach of the nocturnal current to the observation stations (Roshchino-Voyeykov) causes an increase in the variation of the recorded values of the horizontal component as indicated by the magnetometers and to a decrease of the field in the zone of the reflections. If the current strength is such that its location in the immediate vicinity of the reflection zone produces a depression of the reflections (a reduction of the field such that the region of orthogonal reflection is made lower than the level of the level of the ionosphere), the current shift in the latitudinal direction toward the south leads to the production of optimal conditions. At weaker currents, there will not be any depression and we will then observe the reverse picture, in which the distance of the current from the region of the reflections in the southerly direction will lead to a drop in the likelihood of the occurrence of reflections.

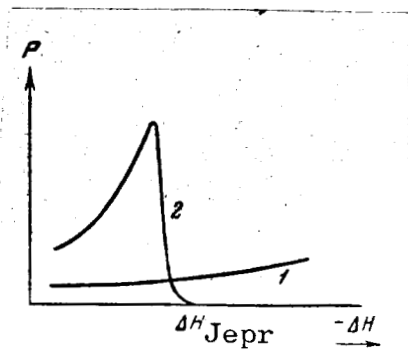


Fig. 15. Change in Probability of Reflections as a Function of Shifting of Currents  $I_1(1)$  and  $I_2(2)$  in the Direction of the Station, i.e., Increase of  $|\Delta H|$ .

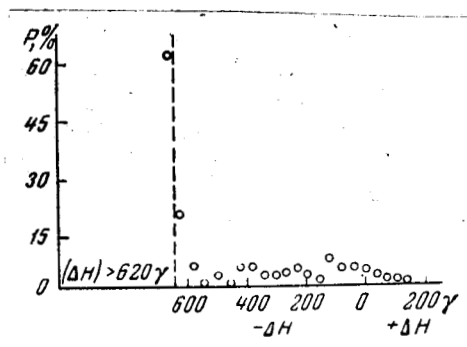


Fig. 16. Experimentally Observed Probabilities of Reflections at the Roshchino Station [23, 73].

<sup>8</sup> See first footnote on page 7.

In order to make the result clearer, let us consider the statistical effect of the joint action of currents with only two possible values. Let  $I_1 < I_2$  where  $I_1$  is the strength of a linear current such that its flow in the optimum proximity to the zone of reflections improves the reflection conditions, i.e., lowers the altitude of the orthogonal reflections for the value 100-110 km. Current  $I_2$  will be considered as being sufficiently strong to cause depression of the reflections when it flows in the vicinity of the zone of reflections, i.e., a drop in the orthogonal altitudes below the level of the  $E$  layer. Let us imagine a current  $I_1$ , shifting gradually toward the south from the original position. Then the dependence of the probability of observation of reflections  $P$  upon the intensity of the magnetic disturbance ( $-\Delta H$ ), determined for this station, will be given by Curve 1 in Figure 15;  $P$  increases as the current  $I_1$  approaches the zone of the reflections, i.e., it becomes larger as the fixed value  $|\Delta H|$  decreases. An analogous relationship for current  $I_2$  is represented by Curve 2.

The values of  $P \approx 0$  when  $|\Delta H| < |\Delta H_{\text{dep}}|$  indicate the appearance of a depression in reflections at periods when the current  $I_2$  is located too close to the zone of reflections and is consequently far from the station. The combined curve will represent the result of the influence of the two currents. It is clear that its nature is similar to the relationship which was obtained experimentally by Pogorelov [73, Fig. 16]. It is possible to think that the interpretation of the results in this sense has a definite basis when we are talking about negative disturbances.

The evening maximum of reflections at Roshchino, related to the daytime segment of the polar current, must be correlated statistically with the positive values of  $\Delta H$ . Unfortunately, Pogorelov /40 did not make a distinction between the times of day in his papers [23, 24]. The lack of reflections for positive disturbances greater than  $\Delta H \cong 160\gamma$  relative to the afternoon maximum, must indicate that the daytime "braid" of the current, located to the north of the region of reflections, produces a significant drop in the altitude of the orthogonal reflections even at rather weak disturbances, while in the case of disturbances that are stronger it leads to depression. A shift of the current to the south, closer to the station (with retention of the same current intensity) leads to the same result. In both cases, this produces the dependence on  $\Delta H$  which was pointed out by Pogorelov.

The Yakutsk Station is also located in the middle latitudes. However, the conditions of the magnetic field in the zone of reflections are completely different for it than for Jodrell Bank and Roshchino. The location is Yakutsk near the maximum of the East Siberian anomaly means that the station is in a position which is to a certain degree different from that of the high latitude stations: it has a characteristically large value of  $Z/H$  both in the region of the station as well as in the zone of the reflections (see Table 2). At the same time, the distance to the active zone for Yakutsk is very great.

The basic data on the statistics of radar reflections at Yakutsk have been published by V. I. Yarin [30], who mentions the existence of two maxima of the occurrence of reflections: in the evening and in the hours following midnight (see Fig. 8). The daytime "braid" of currents, which runs from West to East to the north of the principal region of formation of reflections can only produce an increase in the vertical component of the field, which will cause a worsening of the reflection conditions, since the altitudes for Yakutsk with a quiet field are significantly less than the ionospheric (see Table 2). The occurrence of an evening (afternoon) maximum of reflections at Yakutsk (1700-1800), observed in summer, is possible from this point of view only in the case when the occurrence of some unusual conditions of the daytime current in the W to E direction results in its flowing above the zone of reflections. For Yakutsk, such an occurrence must be rare if we consider that the zone of the auroras is located about 1200 km distant from it, while the daytime segment of the current on the average must be located at more northerly latitudes. In fact, Yarin's data [30] for the winter indicate that the daytime maximum is nearly absent.

The existence of a principal maximum of reflections after midnight (0400-0500), observed during the entire year, shows a regular relationship to the nocturnal current which has the direction E to W. This is clear from the fact that according to the data of V. I. Yarin, the overwhelming majority of radar reflections are observed at negative disturbances of the horizontal component of the magnetic field. Such cases constitute 82% of the total number of reflections, at the same time that the number of positive disturbances, related to currents of opposite direction, is 18%.

All cases of correlation of reflections with negative  $\Delta H$ , according to Yarin, belong to the nocturnal (after midnight) maximum. It is quite clear from this that during those periods when nocturnal reflections are observed at Yakutsk, the system of currents is located to the north of the principal region of reflections. In fact, it is only in this case that the quasi-linear current with the direction E approaches W, which reduces the Z component in the zone of reflections, forms the conditions for raising the region of orthogonal reflections up to the height of the E layer. The shift of the current to closer distances must lead to the opposite effect, since the current, as it flows directly above the region of reflections, produces a drop in the H component of the field. Yarin mentions individual cases of a lack of reflections during magnetic disturbances [30].

The evening reflections (maximum at 1700-1800) occur at Yakutsk much less regularly than do the nocturnal ones, since they nearly disappear at all seasons except Summer. The nocturnal maximum is usually accompanied by magnetic disturbances of much greater intensity (up to 1000  $\gamma$  above the level of a quiet field) than is the evening maximum. The intensity of the reflected signals themselves during the nocturnal hours is also much higher than at all other

times. All of these facts fit very neatly within the framework of the basic system which we have devised. Weak and moderate radar reflections, related to weak magnetic disturbances of both signs [30], admittedly require special attention. The schematic position of the nocturnal current for Yakutsk is represented in Figure 17.

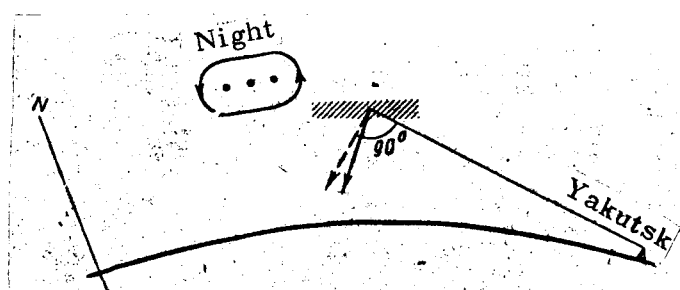


Fig. 17. Position of the Nocturnal Segment of the Current, Stimulating Reflections at Yakutsk. The Symbols Are the Same as in Figure 13.

Let us now turn to a consideration of the Saskatoon Station. According to the data of Currie, Forsyth, and Vawter [12], published in 1953 and dealing with observations made on the frequency of 56 MHz, the reflections begin to appear at Saskatoon at approximately 2000-2100 local time, reaching a maximum at about 2300, after which their number decreases somewhat (with a minimum at about 0300-0600), then rising again approximately until 0700 local

time. Between 0900 and 2000, no reflections are observed (see Fig. 8). The article by Gerson [38], published in 1955, indicates that the curve of the diurnal variation has a somewhat different shape: the minimum occurring after midnight is somewhat less pronounced on it, but the same sharp drop in reflection during the daytime hours is also to be seen there. According to the data of McNamara [36], based on the period of the Winter 1957-1958, the principal maximum of radar reflections occurs in the hours around midnight, with a second somewhat smaller maximum at 0500-0700. In all three cases, the principal maximum of reflections does not occur during the hours after midnight, as at Yakutsk, but in the hours preceding midnight.

In addition, the situation with respect to the constant magnetic field for Saskatoon and Yakutsk is more or less analogous. The values of  $Z/H$  for the Saskatoon Station and the area to the north of it are large, thanks to the proximity of this station to the North American anomaly, so that the altitudes of the orthogonal reflections under undisturbed conditions are much less than the altitude of the  $E$  layer of the ionosphere (see Table 2). Nevertheless, the shift of the maximum in Saskatoon toward earlier hours and the decrease in the number of reflections after midnight are regular. Saskatoon is located approximately 500 km closer to the auroral zone than is Yakutsk. Therefore, the influence of the nocturnal current "braid", drifting toward the south during the first half of the night, begins to exert its influence at Saskatoon earlier than in Yakutsk, so that it comes somewhat earlier than local midnight time (see Table 4).

The decrease in the vertical component of the magnetic field

and the corresponding increase in the region of orthogonal reflections will occur only in the case when the current "braid" is located to the north of the region of reflections. Further motion of the ring current toward the south, taking place during the hours after midnight, would have to produce a drop in the reflections if the shift of the current were sufficiently great. The probability that the current "braid" will be located above the region of reflections or even between it and the observation stations is very great in the case of Saskatoon. This phenomenon can serve to explain the regular minimum in the number of radar reflections at the Saskatoon Station, which is observed soon after midnight. The occurrence of optimum conditions is clearly likely if the ring current moves back again toward the north, which would then lead to the observed increase in the number of reflections at about 0600-0800 local time. /42

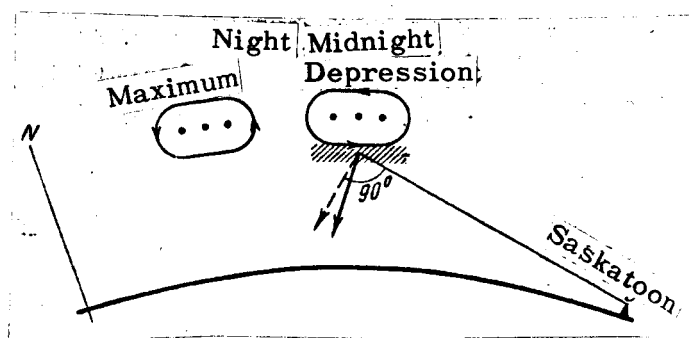


Fig. 18. Distribution of Currents During Stimulation and Depression of Reflections for the Saskatoon Station. Symbols Are the Same as Those in Figure 13.

The corresponding location of the E to W current is shown in Figure 18. The lack of a regular daytime (evening) maximum must be explained for Saskatoon by the same circumstances as at Yakutsk. However, the greater proximity of Saskatoon to the auroral zone implies a greater probability of episodic occurrences of daytime current above the zone of reflections and consequently of daytime (evening) reflections, if only the lack of regular observation of an

evening maximum above Yakutsk is actually related to the polar ring current. It is possible, however, that this is not the case and the evening reflections at Yakutsk have some other cause. Currie et al. [12] and Gerson [38] do not mention the occurrence at Saskatoon of an evening maximum.

It is true that there is no need for a detailed interpretation of the diurnal changes in the number of radar reflections at the other stations located at middle latitudes (see Table 4), since they can be explained analogously. The Kjeler, King Salmon, and Ottawa Stations are located relative to the auroral zone and consequently to the ring current in the same way as the Roshchino Station, while the Ithaca Station is approximately in the same relationship as the Jodrell Bank Station. Therefore, the explanation of the diurnal variation of the radar reflections for the Roshchino and Jodrell Bank Stations can generally be applied to these stations as well.

## Some Regularities of Radar Reflections from Internal Regions of the Polar Cap

As we have shown, the average picture of diurnal variations in the number of observed auroral reflections at stations located at middle latitudes can generally be seen to be in good agreement with the average picture of ionospheric currents in the auroral zone. Although at the present time we do not have at our disposal the required quantitative data, qualitative studies indicate that the hypothesis developed above can be used to get a satisfactory explanation of the diurnal variation of the reflections, the general outlines of the aspect sensitivity, and several characteristic properties of the correlation of radar reflections with disturbances of the magnetic field for these stations. /43

The situation is somewhat different for the stations located at high latitudes, the majority of which are located in the immediate vicinity of the auroral zone and which record reflections which arise within the polar cap. The distinct nature of the diurnal distribution of radar reflections at all of these stations (except the Cape Schmidt Station, for which the statistics are not considerable) there is one or in a few cases two and even three maxima in the diurnal pattern of reflections. The first maximum (frequently the only one) occurs independently of the longitude of the station at approximately the same local time (as a rule, around local midnight); see Table 4 and the shaded rectangle 3 in Figure 9. For all stations of this group, the undisturbed value  $Z/H$  in the region of formation of reflections increases in value since the orthogonal reflections from the ionosphere for these stations are impossible (see Table 2). The Kiruna and Loparskaya (as well as the Farewell) Stations are located under the most favorable conditions, but the undisturbed configuration of the field for them is such that it is only under optimum distances (about 600-900 km) that the region of orthogonal reflections lies at an altitude on the order of 70-90 km.

Is it possible for the distributed current flowing through the polar cap to have any influence on the changes in the parameters of the constant current? If we imagine a current system for the polar cap such that it resembles the one envisioned in the system of Chapman [54] or Vestine (see Fig. 10), any significant influence on its part on the configuration of the constant field in the upper atmosphere at high latitudes must be considered practically impossible, since the current density in the polar cap is obviously insufficiently large for this. On the other hand, the currents of the polar ring current flow on the night side of the Earth during the period of development of a magnetic storm, in the immediate vicinity of stations in this group, and this brings them directly above these stations during a certain period of this time. The regions of formation of reflections for high latitude stations are almost always located within the ring current (within the auroral zone). At optimal distances on the order of 600-900 km, the nocturnal current in the E to W direction must produce a field compo-

nent which increases the vertical component in the zone of reflections. A current with this direction but flowing several hundreds of kilometers to the north of the auroral zone, can be the cause of a reduction in the horizontal component in the zone of reflections. In both cases, this leads only to an additional worsening of the conditions for reflection relative to conditions of an undisturbed field.

It therefore seems to be unavoidable that we must deal with the fact that reflections at the Dikson Island, Cape Schmidt, Barrow and College Stations (the data for which are presented in detail in Tables 2 and 3) and to a lesser degree at the Kiruna and Loparskaya Stations, were obtained under conditions of such strong disturbance of the orthogonal reflection and with such a lack of apparent factors which would be capable of producing these conditions with time, that the generally employed mechanism for formation of reflections for these stations must definitely be taken into account (i.e., if the role of refraction is not as great as suggested in [41, 47]).

The analogous problem under Antarctic conditions was dealt with by R. Bullough, who published a large paper [14] dealing with the study of UFW radar reflections at Dumont-d'Urville, in the region of the magnetic pole. The fulfillment of normal conditions for aspect sensitivity (orthogonality of reflections) at such a geographic position of the station was highly unlikely even in periods of the most severe disturbances. Nevertheless, reflections at a frequency of 73 MHz at the Dumont-d'Urville Station were observed regularly, although the beam angle of the locator with the direction of the constant magnetic field did not exceed  $77^\circ$  for any point in space around the station. Bullough emphasizes that at the Antarctic Station at Holly Bay, as at the stations located at middle latitudes (Jodrell Bank, Saskatoon, and Invercargil in New Zealand, and others) no instances were found when the deviation from conditions of orthogonality was greater than  $3^\circ$  (in all probability, they were less [19, 44]).

We have already mentioned the predominance of occurrence of radar reflections from southern azimuths at the high latitude stations of Baker Lake and Resolute Bay (Canadian Archipelago) [36], which is also in sharp contradiction to the conditions of orthogonal reflection. The same can be said with regard to reflections observed at the Soviet Antarctic Station Vostok [74], located in the region of the geomagnetic pole. All of these facts indicate that in regions near the pole, both in the Northern and Southern Hemispheres, the condition for orthogonality is definitely fulfilled much less strictly than in cases of formation of reflections near the auroral zone (detection of reflections by middle latitude stations).

For interpreting the observations at the Dumont-d'Urville Station, Bullough suggested the theory whose principal element is that the anisotropy of the ionized structures at high altitudes in the  $E$

region can be reduced quite rarely during corpuscular disturbances, which considerably exceed the electron concentration simultaneously a large territory. According to the calculations of Bullough [14], the effect must begin at values of the electron concentration  $n_e > 5 \cdot 10^6 \text{ cm}^{-3}$ . At  $n_e \approx 2 \cdot 10^8 \text{ cm}^{-3}$ , the magnetic field for all practical purposes can no longer produce anisotropy of the electron formations at the level of the E layer, since the diffusion rate of electrons in the lengthwise and transverse directions (relative to the pole) become comparable. If Bullough's interpretation turns out to be correct, it will make it possible not only to explain the occurrence of reflections at the Dumont-d'Urville Station, but also to understand the nature of the anomalous conditions of reflection in general, including those for the Arctic high latitude stations.

The possibility of an alternative interpretation of the phenomenon as being related to the production of sporadic electrical fields and dense current systems within the polar cap is much more doubtful in our opinion. There are apparently no indications of it thus far. On the other hand, the system of quasi-regular distribution of currents, whose lines occupy the entire polar cap with more or less even density and gradually join the two segments of the polar ring current, has received a certain degree of support from the experimental data of the IGY. The regular midnight maximum of reflections at all high latitude stations would clearly be very difficult to relate to the statistically disordered disturbances in the polar cap.

If we use Bullough's interpretation [14], i.e., assuming the possibility of a considerable weakening of the requirement for orthogonality for conditions of high latitude, the stable midnight maximum may possibly be given a rational explanation within the framework of a system which we have used for explaining the diurnal variation of reflections at middle latitude stations. The decrease in anisotropy of the inhomogeneities in highly ionized regions, in Bullough's opinion, leads to final disappearance of the aspect effect only in an extreme case ( $n_e > 10^8 \text{ cm}^{-3}$ ). Since this effect is retained even in a weakened form, the magnetic field continues to have an effect on the geometry of the reflections.

If the scattering diagram for the anisotropic local inhomogeneity is extended from  $2-3^\circ$  to  $30-40^\circ$  (see [5, 13]), the statistically more probable direction of scattering from a given region will still be retained and will be determined primarily by the condition of orthogonality. It is clear that the influence of the nocturnal "braid" of the current, which has the E to W direction and worsens the geometry of reflections from high latitude regions, must grow weaker as the current structure shifts toward the south (in the hours before midnight) and increases again as a result of drift in the opposite direction (in the hours after midnight). This situation is similar for all stations located near the auroral zone. It might lead to the occurrence of the maximum around midnight for reflection as observed at these stations. Long-term variations (as

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well as variations linked to a nonuniform value of  $Z/H$  in the regions of reflections) might exist if one desired to gain information by making a careful comparison of the data from individual stations, but they are not reflected by any statistics which are available at the present time.

The explanation for the maximum occurring around midnight which has been presented for the high latitude stations is not free of contradictions. Thus, the lack of an evening maximum of reflections for a number of high latitude stations has already been pointed out (see Table 4). Under otherwise equal conditions, the daytime current (W to E) would have to cause the occurrence of reflections during the hours of the maximum for this current (1500-1600 local time). In fact, at a number of stations (at Loparskaya, e.g.), these hours see the beginning of a gradual increase in the number of reflections, whose maximum is reached about midnight; at the Tromso and Cape Schmidt Stations, a pronounced maximum in the number of radar reflections is even observed at 1500-1700. The explanation for the lack of a similar maximum at a number of other high latitude stations (Dikson Island, Tixie, and Barrow) clearly calls for a special analysis.

The opinion was expressed in [22] that the absence of this maximum in Kiruna according to the data in [20] was caused by low sensitivity of the apparatus. However, the upper maximum was observed at Cape Schmidt and was lacking at Tixie, and on Dikson Island as well, where identical apparatus was used. It is possible that the reason for the low intensity of the evening reflections was certain differences in the conditions of nocturnal and evening ionization, and even a different influence of the corpuscular intrusion on the nocturnal and evening ionospheres. It is a fact, e.g., that the development of processes of anomalous absorption at high latitudes, following solar flares (Type III) and linked to the development of a magnetic storm (Type II) is such that the symmetry of the daytime and nocturnal sides is disturbed [75, 76].

Hence, to explain the results of the radar observations of the auroral ionization, obtained by different investigators at high latitude stations, it is clearly necessary for us to do away with the requirement of orthogonality for the sounding beam relative to the lines of force of the actual magnetic field at the point of reflection. In this case, the diurnal variations of the frequency of occurrence of radar reflections will be dependent primarily on the conditions of appearance, disappearance, and variation with time of the regions of increased anomaly of ionization. In [22, 33], it was shown that the time of appearance of maxima in the diurnal pattern of radar reflections depends on the latitude and is subject to a law which is usually called the spiral distribution. A. P. Nikol'skiy [77] states that the regions of anomalous ionization are distributed along the isochron of the morning maximum of magnetic activity, and therefore explains the motions of the clouds of anomalous ionization which were observed at the Jod-

rell Bank and Saskatoon Stations. The occurrence of maxima of radar reflections at Saskatoon at 0600-0700 and at Jodrell Bank from 0100-0200 local time (see Table 4) are in good agreement with isochrons of the morning maximum of magnetic activity.

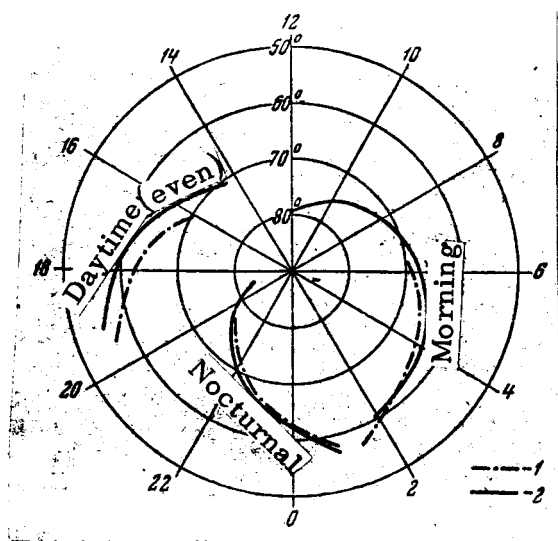


Fig. 19. Spiral Distribution of the Moments of Occurrence of Maxima of Radar Reflections (1) in Comparison to an Analogous Spiral Distribution of the Maxima of Q-Indices of Magnetic Activity (2) During the Summer Season of the IGY, for Magnetically Disturbed Days (According to [80]).

9, using Table 4 as a basis, we have already shown the distribution of periods (in local geomagnetic time) of the maximum values of the frequency of occurrence of radar reflections as a function of the particular geomagnetic latitude. Using the terminology employed in geomagnetism, the maxima can be divided into three groups on the basis of the time of their occurrence: daytime (1500-2000 hrs) nocturnal (2000-2400) and morning (0000-0800). We can see that the time of occurrence of the maxima changes with latitude (the straight lines D, N and M in Fig. 9): the daytime and nocturnal reflections move toward earlier hours when the latitude is increased while the morning maxima shift toward later hours of local magnetic time.<sup>9</sup> As we know, analogous regularities were noticed for the magnetic activity by O. A. Burdo [79].

The qualitative investigation <sup>/46</sup> of the regularities in the occurrence of the peaks in the diurnal pattern of auroral radar reflections, presented in this paper, permits us to draw certain conclusions over a rather wide range of latitudes. Anomalous ionization is produced by the intrusion of charged particles into the upper layers of the atmosphere, thus triggering a number of other phenomena including disturbances of the geomagnetic field. The close relationship between the magnetic disturbances and the occurrence of radar reflections has already been determined in the past.

Using the example of the station located in middle latitudes of the Northern Hemisphere, we attempted to ascertain the finer details of the mechanism of this relationship. It is clear that the regularities in magnetic activity and auroral radar reflections with time must have an identical appearance in several basic intervals on a more general plane. In Figure

<sup>9</sup> Regularity of a similar type was noticed for reflections observed by the two-position method, as reported in [78].

Figure 19 shows the spirals of magnetic activity (according to the  $Q$  indices for the summer season of the IGY for magnetically disturbed days, according to [80]) with corresponding average spirals of radar reflections obtained from Figure 9 with transition to the polar system of coordinates. Selection of magnetically disturbed days was necessitated by the fact that the auroral USW of reflection appear primarily during periods of disturbances. Data on the daytime maximum of radar reflections at the Tromso and Cape Schmidt Stations, as we pointed out earlier, are available only for the summer season. In comparing the magnetic activity and radar reflections, we must keep in mind that the  $Q$  indices of activity characterize the intensity of the electromagnetic processes at the zenith point of the observer. /47

The radar reflections arrive from northern azimuths with a distance on the order of 600-900 km. Therefore, in transferring the data from Figure 9 to Figure 19, the position of a spiral must be shifted  $5-8^\circ$  toward the pole. In Figure 19, the shift is equal to  $5.5^\circ$ <sup>10</sup>. As we can see, the spiral curves of the distribution of maxima of magnetic activity and radar reflections practically coincide with such a shift over the entire range of latitudes. Apparently this indicates that the penetration of corpuscular currents into the upper layers of the atmosphere causes immediate and simultaneous reactions in both the occurrence of geomagnetic activity as well as the appearance of radar USW of reflections.

In conclusion, it should be stated that in studying processes in the ionosphere at high altitudes, the greatest defect is the familiar lack of uniform experimental data, obtained with respect to various aspects of a given complicated situation, which must be viewed as complex by virtue of its nature. Therefore, statements regarding the cause of relationships and the mechanisms of individual phenomena which occurred during the development of this one complex process (though a very difficult one) and the interpretation in a number of cases cannot be carried beyond an analysis of preliminary conclusions.

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<sup>10</sup> Figure 9 shows the periods of maximum values of the frequency of occurrence of radar reflections for all the stations with the exception of Baker Lake and Resolute Bay. The data from the Baker Lake Station provide good information for the nocturnal segments of the spirals (while the Resolute Bay Station provides information of similar quality for the morning segments) with a corresponding reduction in the corrected geomagnetic latitudes. Reduction of the latitudes of these stations is caused by the preferred arrival of radar reflections from southern azimuths.

## Appendix 1

### CALCULATION OF THE SURFACE OF ORTHOGONAL REFLECTION

In the following, formulas are presented for calculating the cross sections of the surfaces of reflection, on the basis of which the altitude values in Table 2 are obtained, and which in the general case can be viewed as the total surfaces of reflection under conditions of a real field. The charts of the magnetic field for 1955, from which the values of the  $H$  and  $Z$  components were taken, were plotted on the basis of data from the Institute for the Study of Terrestrial Magnetism, the Ionosphere, and Radiowave Propagation, Academy of Sciences of the USSR. For all the stations, scale divisions have been marked on the charts to show the distances and azimuths for which the calculation of the altitudes was made.

#### REFLECTIONS IN THE PLANE OF THE MAGNETIC MERIDIAN

The tilt angle  $\alpha$  and the altitude  $h$  of the point of orthogonal reflection are easily found from Figure 20, in which  $P$  is the point at which the station is located;  $S$  is the point of reflection;  $Q$  is the projection of the latter on the surface of the Earth;  $OO'$  is the vertical of the station;  $OO''$  is the vertical of the point of reflection;  $PP'$  is the line of intersection of the horizon of the observer with the meridional plane;  $FF'$  is the tangent to the line of force at the point of reflection;  $PS$  is the beam of the locator;  $OP = OQ = R$  is the radius of the Earth;  $\theta$  is the angle of the line of force with the vertical at the point of reflection;  $QS = h$ ;  $\Delta\phi$  is the distance between  $P$  and  $Q$  in degrees of arc of a great circle. The plane of the diagram is the meridional plane, passing through the verticals of points  $P$  and  $Q$  and containing the magnetic meridian.

Due to the orthogonality of  $PS \perp FF'$ , whence

$$\alpha = \theta - \Delta\phi, \quad (1)$$

$$h = R \left( \frac{\cos \alpha}{\cos \theta} - 1 \right). \quad (2)$$

#### GENERAL CASE

The plane of reflection does not lie in the plane of the magnetic meridian. The tilt angle  $\alpha'$  of the point of orthogonal reflection  $S$  and the altitude of the reflection  $h'$  are calculated from the following considerations (Fig. 21). Let  $PS$  be the radar beam, and  $OO'$  be the vertical passing through the point of reflection  $S$ . Due to the condition of orthogonality, the vector  $F$  lies in the plane  $T_1$  perpendicular to  $PS$ . The plane  $T_2$  perpendicular to  $OO'$  contains the vector of the horizontal component  $H$ . The vector angle  $H$  with the plane  $PSO'$  is equal to  $\omega$ . The vector of the vertical component is directed along  $OO'$  and forms angle  $\kappa$  with plane  $T_1$ . The angle between the horizontal plane  $T_2$  and the plane  $T_3$ , contain-

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If we omit the subsidiary angle  $\psi$  from (3) and (4), we will have the relationship:

$$\operatorname{tg} \kappa = \operatorname{tg} \theta \cdot \cos \omega. \quad (5)$$

For determining the tilt angle  $\alpha$  in the case of the meridional plane, /49 we used relationship (1). In this case, when the locator beam does not lie in the plane of the magnetic meridian, the tilt angle  $\alpha'$  is determined by the formula

$$\alpha' = \kappa - \Delta\varphi, \quad (6)$$

while the altitude

$$h' = R \left( \frac{\cos \alpha'}{\cos \kappa} - 1 \right). \quad (7)$$

By determining  $\kappa$  from (5) and substituting into (6), we are able to find the local angle of the point of orthogonal reflection for any point in space at which  $\theta$  is given (or the magnetic declination  $90^\circ - \theta$ ) and  $\omega$  (the difference between the azimuth at the reflection point and the magnetic deviation at the same point, and we can also find the altitude  $h'$  according to Formula (7).

By combining (5), (6) and (7) and expressing  $\omega$  by means of the deviation ( $\delta$ ) and the azimuth of the beam ( $\varepsilon$ ), we obtain a system of equations suitable for calculating the position of the surface of the orthogonal reflection, using as a basis the picture we have formed of a real field:

$$\begin{aligned} \varepsilon - \delta &= \omega, \\ \operatorname{tg} \theta \cdot \cos \omega &= \operatorname{tg} \kappa, \\ \alpha' &= \kappa - \Delta\varphi, \\ h' &= R \left( \frac{\cos \alpha'}{\cos \kappa} - 1 \right). \end{aligned} \quad (8)$$

The angle  $\kappa$  in this system is essentially an auxiliary one, but it does not have a clear physical significance; this is the angle between the vertical at the reflection point and the reflecting plane containing the vectors  $H$  and  $Z$  of this point.

It is obviously not a difficult matter to combine system (8) into a single equation for the surface of orthogonal reflections, by means of which the altitude of the point of reflection  $h'$  will be expressed as a function of the distance ( $\Delta\phi$ ), the azimuth of the reflection point ( $\varepsilon$ ) and the parameters of the magnetic field at the point of reflection: the deviation ( $\delta$ ) and the angle of the line of force formed with the vertical ( $\theta$ ).

$$h' = R \{ \cos [\arctg (\operatorname{tg} \theta \cdot \cos \omega) - \Delta\varphi] \cdot (\operatorname{tg}^2 \theta \cos^2 \omega + 1)^{1/2} - 1 \}, \quad (9)$$

where  $\omega = \varepsilon - \delta$ . However, a clear expression of this function is not of great interest since practical calculations can make equally good use of Equations (8).

The method described above for calculating the surface of orthogonal reflections is simpler than the method described earlier by Ye. A. Ponomarev [29].

## AZIMUTHS AT THE DIKSON ISLAND STATION

At high latitudes, owing to the fact that the vertical component of the field  $Z$  is much greater than the horizontal component  $H$ , the size of the locus decreases so that the reflections from the lateral directions within the framework of Chapman's theory become impossible. If the field of the deviations leads to the same inhomogeneity as in the regions to the north of the Dikson Island Station, the conditions for reflection become still worse. Thus, e.g., for the Dikson Island Station at an azimuth of about  $45^\circ$  to the west of the direction of the geographical north, the beam forms an angle  $\omega \approx 90^\circ$  with the direction  $H$ . The fulfillment of the condition of orthogonality is then impossible of course.

Let us calculate the permissible values of  $\omega$  for a level of altitude on the order of 100 km. At a distance  $L = 900$  km ( $\Delta\phi = 8^\circ 6'$ ) for the given altitude  $\alpha' \approx 2^\circ$ , we find [according to Equation (6)], the angle  $\kappa = \alpha' + \Delta\phi$  close to  $10^\circ$ . The maximum value of  $\theta$  for all these regions (see Table 2) is about  $20^\circ$ . Using Formula (5), we find that for  $L = 900$  km,  $\omega$  cannot exceed  $60^\circ$ . However, in the region to the north of Dikson Island,  $\theta$  can be much less than  $20^\circ$ , and this makes reflections from lateral azimuths completely inexplicable, even if we assume that the orthogonal reflections from an altitude of 100 km are possible in a meridional plane with  $\omega = 0^\circ$ . As we pointed out earlier, in the case of Dikson Island and other high latitude stations, this difficulty also extends to reflections in the meridional plane.

## Appendix 2

### APPROXIMATION OF THE RESIDUAL FIELD IN THE ARCTIC REGIONS

In Figure 7, an attempt has been made to approximate the plane residual field over a considerable range of two geomagnetic meridians by means of the minimum number of dipoles. The residual field is obtained by calculating the  $H$  and  $Z$  components of the field of the central dipole with a magnetic moment  $M_0 = 8.25 \cdot 10^{25}$  CGSM, from the corresponding components of the real field, whose isodynes are shown in Figures 22 and 23. The magnetic field for 1955 is taken /50 from the charts of the Institute for the Study of Terrestrial Magnetism, the Ionosphere, and Radiowave Propagation, Academy of Sciences of the USSR, plotted by V. P. Orlov, and located in the World Data Center B2. The charts which are presented do not include the polar regions, so that checking the isodynamic lines of the horizontal component was carried out on the basis of the schematic chart of the Arctic and Antarctic Scientific Research Institute in 1954 [81]. For the isodynamic lines of the vertical component in the polar regions, there was no such check, and they were drawn more or less provisionally.

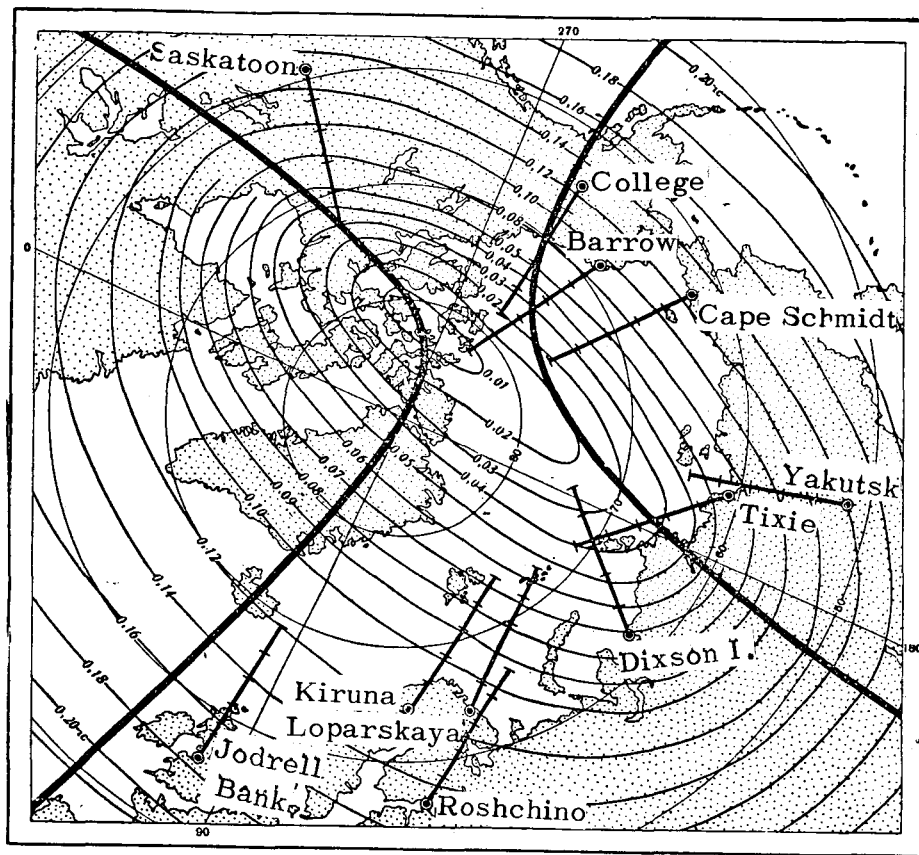


Fig. 22. Isodynamic Lines of the Horizontal Component of the Magnetic Field (for 1955), with Indication of the Directions in Which the Altitudes of the Orthogonal Reflections were Calculated, Appearing in Table 2. The Heavy Lines are the Zero Isogons, Calculated Relative to the Geomagnetic Pole.

TABLE 5

| Dipole | Coordinates of the point of intersection of the dipole axis with the surface of the Earth |                        |                        | Distance of the dipole from the surface of the Earth in units of the Earth's radius) | Magnetic Moment of the dipole (CGSM) | Maximum value of $Z$ formed by the dipole with the surface of the Earth, in Gauss |
|--------|-------------------------------------------------------------------------------------------|------------------------|------------------------|--------------------------------------------------------------------------------------|--------------------------------------|-----------------------------------------------------------------------------------|
|        | $\lambda, ^\circ\text{E}$                                                                 | $\phi, ^\circ\text{N}$ | $\phi, ^\circ\text{N}$ |                                                                                      |                                      |                                                                                   |
| ESA    | 101                                                                                       | 44                     | 38                     | 0.51                                                                                 | $0.30 \cdot 10^{25}$                 | 0.180                                                                             |
| NAA    | 262                                                                                       | 42                     | 51                     | $\sim 0.4$                                                                           | $0.05 \cdot 10^{25}$                 | 0.066                                                                             |
| IGA    | 333                                                                                       | 70                     | 76                     | $\sim 0.5$                                                                           | $0.16 \cdot 10^{25}$                 | - 0.100                                                                           |

The approximation which satisfactorily describes the residual field over a considerable extent of the length of the meridians ESA and NAA, including a circumpolar region, obtained by using the theories regarding the three dipoles corresponding to the principal portion of the residual field of the East Siberian, North American and Iceland-Greenland anomalies (the latter anomaly is negative). In Table 5, we have listed the parameters of these three dipoles, on the basis of which the curves in Figure 7 were plotted.

As we can see from Figure 7, superposition of corresponding components of the three dipoles permits us to get a satisfactory idea of the nature of the field in the regions of Arctic latitudes on the ESA and NAA meridians. Selection of parameters of the dipoles is not completely unambiguous so that the results presented in Table 5 and Figure 7 must be viewed only as one of a variety of approximations which may not be entirely correct. It is important to point

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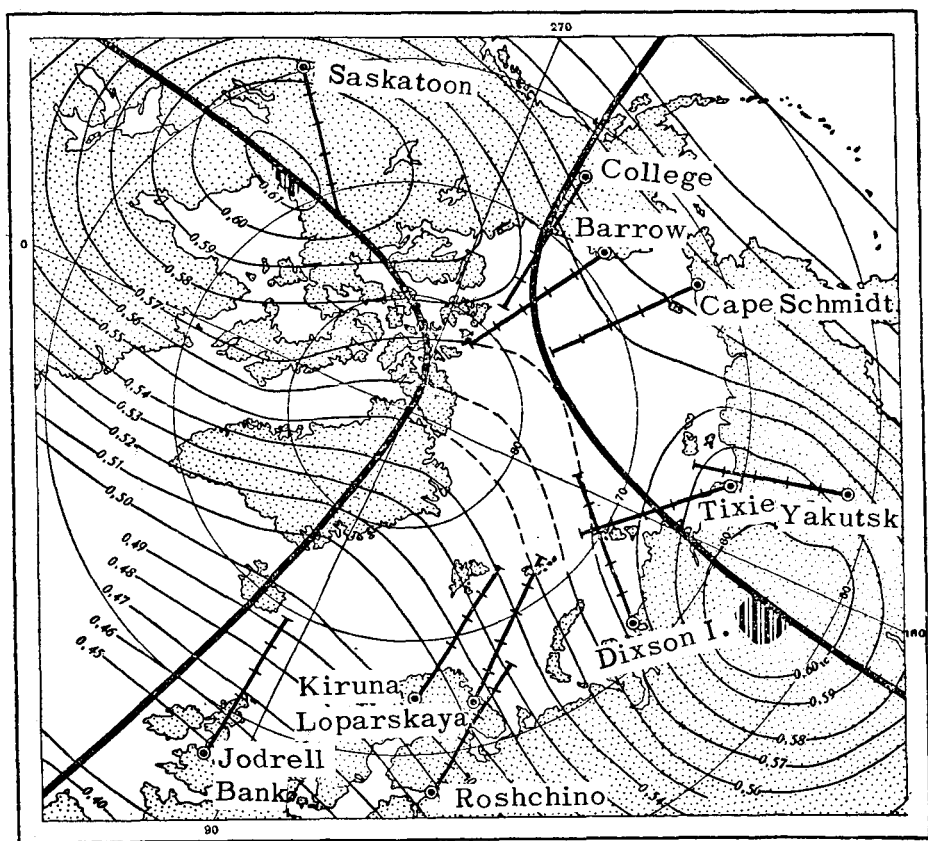


Fig. 23. Isodynamic Lines of the Vertical Component of the Magnetic Field (for 1955) with Indication of the Directions in Which the Altitudes of the Orthogonal Reflections Shown in Table 2 Were Calculated. The Heavy Lines are the Zero Isogons, Calculated Relative to the Geomagnetic Pole. The Shaded Areas Are Centers of Magnetic Anomalies.

out that the depths at which the dipoles are located, which are responsible for the entire residual field at high latitudes, are very great so that the constant field at ionospheric altitudes cannot differ significantly from the field at the Earth's surface. In Figure 24, we have shown the values of the  $X$  and  $Z$  components of the residual field at points along the geomagnetic meridian passing through the center of the Iceland-Greenland anomaly in comparison to the values of the  $H$  and  $Z$  components of the dipole field of the IGA at the same points. The deviation is minimal at high latitudes. At lower latitudes, on the same meridian, it is necessary to make a correction which takes into account the existence of the African anomaly on the one hand and the weak negative anomaly in the vicinity of the Aleutian Islands on the other.

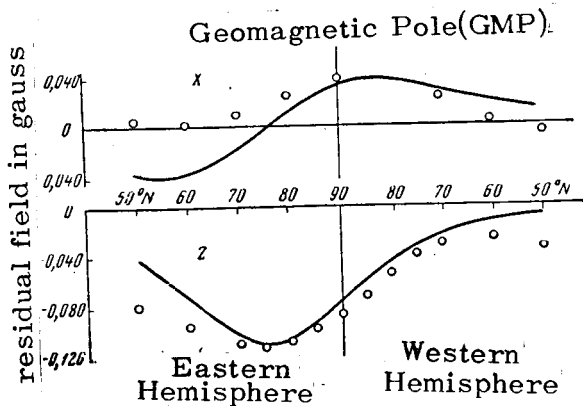


Fig. 24. Components of the Residual Field at Points Along the Geomagnetic Meridian of the Iceland-Greenland Anomaly (Circles) and Their Approximation by the Dipole IGA (Heavy Line). GMP Equals Geomagnetic Pole.

## CONCLUSIONS

1. Azimuthal distribution of reflections received at stations /52 for the radar study of aurorae, at frequencies with a range of one meter, was studied in this paper. The preferable azimuths for stations in the northern hemisphere were compared with the direction of the magnetic field at the Earth's surface. For the majority of them, there was found a symmetry in the arrangement of the preferable zones for formation of reflections relative to the direction of the real magnetic field. The most significant divergences from this rule are given from stations which are located close to the center of the East-Siberian anomaly of the vertical component (Tixie Bay, Yakutsk).

2. On the basis of the symmetry for the reflection zones relative to the field, we can choose one out of two assumptions on the character of the magnetic field at altitudes for reflection formation of 100-110 km. In correspondence with the calculations of a number of other authors, the active field is considered the real (local) one, and not the geomagnetic. This selection also agrees with direct measurements of the magnetic field at altitudes on the order of 300 km, with the aid of the third artificial Earth satellite.

3. For a self-containing argument in favor of the preceding assumption, we examined the division of the real field for high Arctic latitudes into the following components: the field of the central dipole, the field of effective dipoles for the East-Siberian anomaly, the North-American anomaly, and the negative Icelandic-Greenlandic anomaly. To such a degree as it is possible that the mentioned decomposition can serve as proof of the deep-seated derivation of the remanent field for the northern regions of the northern hemisphere, it is justifiable to take the real field as an active one for these regions at altitudes on the order of 100-110 km.

4. Assuming that the field is real, we calculated the theoretical heights of orthogonal reflection for all the stations being studied. The results of the calculations were made for distances from 300 to 1500 km from the station in the direction toward the preferable azimuth of the reflections, without considering refraction of the beam. For the high-latitudinal stations in Europe, Asia, and the North-American coast of the Arctic Basin, as well as for some of the average-altitudinal stations, the theoretical calculated heights of the reflections (under conditions for calculating the real field) were much lower than the ionospheric altitudes. This made the systematic observation by all these stations inexplicable for the reflections from altitudes of 100-110 km, if we consider only the conditions for a static field. (The probability of a significant distortion of the ray trajectory as a result of refraction is considered small.) Only for a small number of sta-

tions (Jodrell Bank, Roschino, King Salmon) were the conditions for orthogonal reflection fulfilled over a limited distance range which, however, was much less than the range for the distances being observed.

5. In order to explain the possibility of existence of orthogonal reflections over a wide distance range at average-latitudinal stations, we used a hypothesis on a distortion of the magnetic field lines in the zone of reflection formation during periods of magnetic disturbances. The polar current flowing at an altitude of about 100 km was examined as the real source of magnetic disturbances which reach maximum intensity near the auroral zone, and which determine the dimensions for the structure of the magnetic field in the reflection zone. /53

6. A consecutive change during the course of disturbed days in the polar current of the eastern direction ( $W \rightarrow E$ ) to the current of the western direction ( $E \rightarrow W$ ) and the drift of these currents, toward the South before local midnight and to the North after midnight, are explained by statistical rules for the diurnal path of probability of the occurrence of radar reflections at average-latitudinal stations from ranges close to the auroral zone (Jodrell Bank, Roschino, Yakutsk, Saskatoon, Kjeler, Ottawa, King Salmon, Ithaca). Correlation between the diurnal path of radar reflections and the general character of the disturbances of the diurnal variation, with a change in the sign of irregular disturbances in the auroral zone, and partly with the intensity of the magnetic activity at average-latitudinal stations, can be satisfactorily explained by this hypothesis.

7. In view of the insufficient amount of materials from radar observations, this explanation for the diurnal path of radar reflections and for their correlation with magnetic disturbance (for average-latitudinal stations) can still be only within the framework of the statistical picture of radar reflection observations. However, it is obvious that we must also consider the picture of the auroral part of the current system of a magnetic storm, on the basis of which lie Chapman's assumptions ( $SD$ -variation), to be statistically valid. A study of the magnetograms from high-latitudinal observatories indicates that there are sharp disturbances in the continuity of development of a magnetic disturbance, as a factor which is characteristic of occurrences in the regions which are located along the auroral zone. A development of the features of a detailed correlation between radar reflections and magnetic activity requires expansion of the number of radar observations.

8. An explanation of the diurnal path (which, by the way, is a fact to a great degree) of auroral radar reflections at high-altitudinal stations on the basis of orthogonal reflections encounters great difficulties. Taking the distributed current of the polar cap (the type of Chapman's diagram) as a factor which makes it possible for high-latitudinal stations to receive radar reflec-

tion altitudes of 100-110 km, obviously does not bring about the necessary result. The role of ring current drift is briefly discussed. The assumption on the destructions of the "aspect-effect" at high latitudes, particularly Bullough's hypothesis, suggested for interpreting auroral echo observations at Terre Adelie (Antarctica), is examined as a more probable solution.

9. The investigation of statistical rules for radar reflections clearly shows that, besides the geometrical factor (the condition of orthogonality), the facts of appearance and disappearance of anomalous ionization in the regions of formation of reflected signals greatly influence the statistical regularities of radar reflections. Space-time distribution of radar reflections coincide well with analogous statistics which were found previously for magnetic activity. The time of maximum occurrence of reflections (in their daily variation) depends on latitude, obeying the regularity which is usually called a "spiral distribution". The time of maximum occurrences of day and night reflections shifts to earlier hours when the latitude increases, and the time of morning reflections shifts to later hours of the local geomagnetic time.

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Translated for the National Aeronautics and Space Administration by:  
Aztec School of Languages, Inc.,  
Research Translation Division (306)  
Acton, Massachusetts  
NASw-1692